TP 10050E

STATE OF THE ART REVIEW OF PRESSURE LIQUEFIED GAS CONTAINER FAILURE MODES AND ASSOCIATED PROJECTILE HAZARDS

Prepared for
Transportation Development Centre
Policy and Coordination Group
Transport Canada
August 1989

CA1
DTR290-
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S707

Department of Mechanical Engineering
Queen's University
Kingston, Ontario, Canada

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by
I.R.M. Leslie
and
A.M. Birk

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Department of Mechanical Engineering
Queen's University
Kingston Ontario

DDN 4/61660

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Un sommaire en français de ce rapport est inclus avant la table des matières.

Transport Canada / Transports Canada

PUBLICATION DATA FORM

1. Transport Canada Publication No.	2. Project No.	3. Recipient's Catalogue No.
TP 10050E	7215	

4. Title and Subtitle

STATE-OF-THE-ART REVIEW OF PRESSURE LIQUEFIED GAS CONTAINER FAILURE MODES AND ASSOCIATED PROJECTILE HAZARDS

5. Publication Date: August, 1989

6. Performing Organization Document No.:

7. Author(s): **I.R.M. Leslie and A.M. Birk**

9. Performing Organization Name and Address:
Department of Mechanical Engineering
McLaughlin Hall, Queen's University
Kingston, Ontario K7L 3N6

8. Transport Canada File No.: D1465-302-6-7

10. DSS File No.: 14SD.T8200-8-8555/A

11. DSS or Transport Canada Contract No.: T8200-8-8555/01-SD

12. Sponsoring Agency Name and Address:
Transportation Development Centre (TDC)
200 René-Lévesque Blvd. West
West Tower, Suite 601
Montreal, Quebec H2Z 1X4

13. Type of Publication and Period Covered: Tech.;Feb.-Sept.1989

14. Project Officer: **D.W. Dibble**

15. Supplementary Notes (Funding programs, titles of related publications, etc.)

16. Abstract

The purpose of this study was to investigate what is known about the failure of pressure liquefied gas transport and storage tanks. A comprehensive literature search and review has been carried out to assess the level of knowledge relating to the causes and characteristics of vessel ruptures. Specific parameters of interest were: the effect of vessel initial conditions (fill level, initial temperature etc.) on rupture severity; the ability to predict the occurrence of boiling liquid expanding vapour explosions (BLEVE); and the effects of explosions such as blast wave and missile generation.

This literature review revealed that there are several areas where our knowledge is weak. These areas include: the effects of blast on structures, the prediction of the hazards from, and the size of, fire balls, and the understanding of failure modes of pressure liquefied gas containers.

This report identifies areas requiring further research. It was concluded that an experimental program should be initiated to investigate the effects of container size, shape and lading condition on the consequences of a vessel rupture.

17. Key Words	18. Distribution Statement
Liquefied Gas Tanks, Containers, Vessels, Rupture, Explosion, Failure	Limited number of copies available from the Transportation Development Centre

19. Security Classification (of this publication)	20. Security Classification (of this page)	21. Declassification (date)	22. No. of Pages	23. Price
Unclassified	Unclassified	-	xx, 84	-

TDC/CDT 79-005
Rev 88

Canada

Transports Canada Transport Canada

FORMULE DE DONNÉES POUR PUBLICATION

1. N° de la publication de Transports Canada: **TP 10050E**	2. N° de l'étude: 7215
3. N° de catalogue du destinataire:	
4. Titre et sous-titre: **STATE-OF-THE-ART REVIEW OF PRESSURE LIQUEFIED GAS CONTAINER FAILURE MODES AND ASSOCIATED PROJECTILE HAZARDS**	5. Date de la publication: Août, 1989
	6. N° du document de l'organisme exécutant:
7. Auteur(s): **I.R.M. Leslie et A.M. Birk**	8. N° de dossier — Transports Canada: D1465-302-6-7
9. Nom et adresse de l'organisme exécutant: Department of Mechanical Engineering McLaughlin Hall, Queen's University Kingston, (Ontario) K7L 3N6	10. N° de dossier — ASC: 14SD.T8200-8-8555/A
	11. N° de contrat — ASC ou Transports Canada: T8200-8-8555/01-SD
12. Nom et adresse de l'organisme parrain: Centre de développement des transports (CDT) 200 ouest, boul. René-Lévesque Tour ouest, suite 601 Montréal, (Québec) H2Z 1X4	13. Genre de publication et période visée: Tech.;fév.-sep.1989
	14. Agent de projet: **D.W. Dibble**

15. Remarques additionnelles (Programmes de financement, titres de publications connexes, etc.)

16. Résumé

La présente étude avait pour objectif d'examiner les données connues au sujet de la défaillance des réservoirs de stockage et de transport de gaz liquéfié sous pression. Une recherche documentaire exhaustive et un examen de cette documentation on été effecturés afin de déterminer l'étendue des connaissances actuelles sur les causes et caractéristiques de rupture des réservoirs. Les points étudiés comprennent: les relations entre les conditions initiales à l'intérieur d'un réservoir (niveau de remplissage, température initial, etc.) et la gravité de la rupture; la possibilité de prévoir les explosions dues à la dilatation des vapeurs de gaz liquéfié en ébullition; les effets de l'explosion; l'onde de choc et la projection de fragments par exemple.

L'examen de cette documentation a révélé que nos connaissances sont limitées sur plusieurs aspects du problème parmi lesquels les conséquences de l'explosion sur les structures, les dangers que représentent les boules de feu et les dimensions de ces boules, ainsi que les modes de défaillance des réservoirs de gaz liquéfié sous pression.

Ce rapport indique les aspects qui doivent faire l'objet d'une recherche plus poussée. En conclusion, il propose de lancer un programme expérimental visant à examiner les conséquences de la rupture d'un réservoir en fonction de ses dimensions, de sa forme et de l'état de sa cargaison.

17. Mots clés: Réservoirs de gaz liquéfié, rupture, explosion, défaillancd.	18. Diffusion: Le Centre de développement des transports dispose d'un nombre limité d'exemplaires.

19. Classification de sécurité (de cette publication)	20. Classification de sécurité (de cette page)	21. Déclassification (date)	22. Nombre de pages	23. Prix
Non classifiée	Non classifiée	-	XX, 84	-

CDT/TDC 79-005
Rev 88

Canada

SUMMARY

This study was conducted to evaluate the state of knowledge of predicting the modes and the effects of the failure of pressure liquefied gas (PLG) containers. PLGs are substances, such as propane and chlorine, that under atmospheric conditions are gases, but for transportation and storage are liquefied by pressurization. These containers hold a great deal of energy and an accident can result in an explosion. The most severe form of these explosions is called a boiling liquid expanding vapour explosion (BLEVE). If the released commodity is flammable then a fire ball can result. PLG containers of specific interest in the study were rail tank cars, highway tank trucks and stationary storage vessels.

Improvements in transportation safety of PLGs have been made recently. The American Association of Railroads (AAR), the U.S. Department of Transport (DOT) and Transport Canada (TC) have all conducted research and taken regulatory action to reduce the number of serious accidents in rail transport. Storage tank yards have shown a good record in terms of accident occurrences. However, when accidents occur in either of the above situations the results can be extreme. Therefore it is important to have a good understanding of the mechanisms involved when PLGs are released in accident situations. This type of information is important for designers and planners as well as emergency response personnel.

The work conducted by the AAR, FRA, DOT and TC has addressed the means to prevent or reduce the likelihood of accidents and unwanted releases. The present study involved a literature search and review of our ability o predict the resulting hazards from a PLG container failure in the event of an accident. Specific ares of interest were: the effect of container and lading conditions on rupture severity, the ability to predict BLEVEs and the hazards from accidental releases such as explosions and missile generation.

Based on the results of this study it is clear that there is a need to carry out research to answer many questions about the hazards of PLG container failure. The following observations are based on the results of the literature search

and review:

1) There is generally a better understanding of pressurized gas container failure that pressure liquefied gas container failure.

2) The accuracy of predicting fire balls from BLEVE events is poor. While there are many validated models for predicting non-BLEVE fire balls, none have shown validity specifically for BLEVE events.

3) Prediction methods exist to calculated the effects of blast on structures. However, when the blast results from a BLEVE, large uncertainties remain.

4) There is no ability to predict the failure modes of PLG storage tanks. However, data has been collected that can indicate the likelihood of a particular failure mode occurring.

5) No validated model exists to predict the hazards from projectiles generated from PLG container failure.

6) The effects of the fill level or lading conditions in the PLG vessel, at the time of rupture, on the severity of the explosion have not been investigated.

7) Several theories for the mechanism of BLEVEs have been advanced but no experimental evidence has been used to support them.

It is important to develop a better understanding of the mechanisms involved with the generation of a BLEVE type release since these are the most violent forms of PLG releases. Work should be conducted to help understand the characteristics of fire balls from BLEVE events. More data is needed to predict failure modes of PLG containers. A validated model for the prediction of projectile hazards should be developed.

Based on the results of this study it is clear that research is needed to obtain a better understanding of PLG release modes and mechanisms. The following recommendations are made:

1) Experiments are needed to generated data necessary for the development and validation of models. These experiments should involve actual fire testing of PLG tanks and should include specific studies of fill levels and lading conditions at rupture. Data obtained from such tests should include a detailed summary of the container failure; severity and extent of release; and the percentage of lading remaining after the initial release event.

2) Whenever possible, accident reports should include details of the condition of the failed container and the severity of the release.

3) Models should be developed so that designers, planners and regulators can incorporate the results of the above tests into practice.

4) A theory needs to be developed, supported by evidence, to explain the mechanism of a BLEVE. This theory should explain what causes a BLEVE, the mechanism by which it occurs and what parameters influence its occurrence. With such information it may one day be possible to design "BLEVE suppressors", or at least improve vessel designs to reduce the occurrence of BLEVEs.

SOMMAIRE

La présente recherche a eu pour but de faire un tour d'horizon des techniques de prévision des modes de ruine des enceintes contenant des gaz liquéfiés sous pression (GLP) et des conséquences possibles. Les GPL sont des substances qui, à la pression atmosphérique normale, sont des gaz mais qui, pour les besoins de leur transport et stockage, sont liquéfiés sous pression (exemple, le propane et le chlore). Les enceintes utilisées doivent pouvoir résister aux pressions intérieures, faute de quoi, tout incident risque d'entraîner une explosion. La forme d'explosion la plus redoutable est due à la dilatation brutale des vapeurs d'un gaz liquide en ébullition, communément appelée BLEVE. Si, en plus, ce gaz est inflammable, alors la formation d'une boule de feu est une conséquence possible. Les enceintes dont il est question ici sont les wagons et les camions citernes et les réservoirs fixes.

Le transport des GLP est devenue beaucoup plus sûr récemment: l'American Association of Railroads (AAR), le Department of Transport des États-Unis et Transports Canada, ont tous mené des recherches et produit des règlements visant à réduire le nombre des accidents graves en transport ferroviaire. Quant au nombre d'accidents survenus dans les parcs de réservoirs fixes, il peut être considéré acceptable. Cela dit, lorsqu'un accident arrive, les conséquences peuvent être terribles. Il est donc impératif d'approfondir nos connaissances des mécanismes qui se déclenchent lorsque, à la suite d'un accident, les GLP commencent à se répandre, connaissances indispensables tant aux projeteurs et aux planificateurs qu'aux effectifs d'intervention.

Les recherches menées par les organismes précités ont porté sur les moyens susceptibles de prévenir les accidents, ou du moins d'en atténuer les effets. Pour cela, une recherche documentaire et un tour d'horizon ont été faits sur les techniques connues permettant de mettre en évidence les dangers qui peuvent résulter d'un accident et de la ruine subséquente d'une enceinte contenant du GLP. Les secteurs ainsi approfondis ont été: l'influence de l'état de l'enceinte et de la cargaison sur l'étendue de la rupture, la prévisibilité d'une BLEVE et des dangers qui peuvent en résulter, telles les explosions et la projection de gros fragments.

L'étude a montré le besoin flagrant de recherches approfondies sur les divers aspects de la question des dangers dus à la ruine d'une enceinte contenant du GLP. Voici quelques remarques fondées sur les résultats de la recherche documentaire et du tour d'horizon technique:

1) Les mécanismes de ruine sont maintenant mieux connus dans le cas des enceintes à pression de gaz que dans celles à pression de gaz liquéfié.

2) La prévisibilité d'une BLEVE accompagnée d'une boule de feu souffre de grandes imprécisions. Alors qu'il existe de nombreux modèles fiables pour prévoir les explosions autres que les BLEVE, aucun n'a encore été validé dans le cas d'une BLEVE proprement dite.

3) Il existe des techniques de prévision et de calcul des effets d'une explosion sur une structure mais, dès qu'il s'agit d'une BLEVE, les résultats sont largement insuffisants.

4) Aucune technique connue ne permet de prévoir avec exactitude le mode de ruine d'un réservoir de GLP. Ce que les données recueillies permettent maintenant de calculer, ce sont les probabilités de tel ou tel mode de ruine.

5) Aucun modèle ne peut fiablement calculer les risques associés à la formation et la projection de fragments à la suite d'une rupture brutale d'une enceinte contenant du GLP.

6) L'effet du niveau de remplissage ou de l'état de la cargaison à l'intérieur de l'enceinte sur l'intensité de l'explosion au moment de la rupture n'a pas été approfondi.

7) Plusieurs théories ont été édifiées pour expliquer le mécanisme d'une BLEVE mais aucune n'a été supportée par des expérimentations.

Il est impératif d'approfondir les mécanismes donnant lieu à une BLEVE qui est la forme d'explosion de réservoirs de GPL la plus violente de toutes, ainsi que les caractéristiques des boules de feu consécutives à une BLEVE. En outre, il faut étoffer les données de prévision des modes de ruine des enceintes et réaliser un modèle faible pour le calcul des risques inhérents à la formation et la projection de fragments lors d'une rupture brutale.

Les résultats de l'étude entreprise montrent clairement l'importance des recherches visant à élucider les modes et les mécanismes de ruine des enceintes pour GLP. Ils permettent de faire les recommandations suivantes:

1) Lancer des expérimentations visant à enrichir la base de données nécessaire à la mise au point et la validation de modèles de prévision. Réalisées à diverses échelles, elles doivent mettre en oeuvre des enceintes soumises à l'action des flammes et éclairer l'influence du niveau de remplissage et de l'état de la cargaison sur l'intensité de l'explosion au moment de la rupture. Les résultats, très détaillés, doivent indiquer le mode de rupture, la taille des fragments projetés, les distances atteintes, l'intensité et l'étendue de l'explosion, et la quantité en pourcentage des gaz subsistant dans l'enceinte après l'explosion.

2) Les comptes rendus d'accidents doivent, dans la mesure du possible, décrire en détail l'état de l'enceinte éclatée et la force de l'explosion.

3) Réaliser des modèles qui permettent aux projeteurs, planificateurs et organismes de réglementation de tirer parti des résultats des essais précités.

4) Il faut édifier une théorie raisonnée expliquant le phénomène des BLEVE: causes, évolution et paramètres importants. Forts de cette théorie, les projeteurs pourront peut-être un jour concevoir des dispositifs de prévention d'explosions du type BLEVE ou, du moins, parviendront-ils à perfectionner les enceintes sous pression de manière à réduire les risques de BLEVE.

Table of Contents

page

1-0 INTRODUCTION

1-1 Background 1
1-2 Objective and Scope 5

2-0 LITERATURE SEARCH

2-1 Overview and Sources of Information 6
2-2 Experimental Studies 6
2-3 Modelling Studies 7
2-4 Case Studies 9
2-5 Theory 10

3-0 DISCUSSION

3-1 Experimental Studies

3-1-1 Fire Impingement 11
3-1-2 Flashing Liquid 16
3-1-3 Blast Overpressure 18

3-2 Modeling Studies

3-2-1 Thermal Modelling 29
3-2-2 Fire Ball Modelling 30
3-2-3 Projectile Modelling 33
3-2-4 Blast and Missile Effects on Structures Modelling 43

3-3 Case Studies

3-3-1 Fill Conditions 58
3-3-2 Projectiles 59
3-3-3 Case Studies Compared to Experimental Studies . 61
3-3-4 Blast Overpressure 63
3-3-5 Fire Ball 64

3-4 BLEVE Theory 68

4-0 RESEARCH NEEDS

4-1 Projectile Hazards 72
4-2 Blast and Projectile Effects on Structures 72
4-3 Vessel Failure Modes 73

Table of Contents continued

page

4-4 BLEVE Phenomena 73
4-5 Fire Ball Hazards 74

5-0 CONCLUSIONS AND RECOMMENDATIONS 75

REFERENCES 79

List of Tables

page

Table 1: Fire Impingement Tests 22

Table 2: Flashing Liquid Experiments 26

Table 3: Fire Ball and Blast Overpressure Experiments 27

Table 4 Fire Impingement Modelling 49

Table 5: Programs for Fire Impingement Modelling from Moodie(1988) revised by the authors 50

Table 6: Fire Ball and Blast Overpressure Modelling 51

Table 7: Modelling of Projectiles 52

Table 8: Blast and Missile Effects on Structure Modelling . . 55

Table 9: Case Studies 65

Table 10: Theory 71

List of Figures

page

Figure 1: Total Number of Accidents in Which There was a Release of Hazardous Materials (CTC Railway Transprot Committee Operations Branch, 1986) 2

Figure 2: Fire Induced Ruptures of 112(114) Cars Before and After Retrofit Programs (Phillips, 1985) . . . 2

Figure 3: Chain of events for a pressure liquefied gas container accident 4

Figure 4: Wall temperatures for a 1/5 scale test 12

Figure 5: Shell Fracture Pattern For the Uninsulated Tank Car (Manda, 1974) 13

Figure 6: Simple scaling of vapour cloud explosion experiments for partially confined obstacles (Van Wingerden and Zeeuwen, 1980) 20

Figure 7: Flame distance from source against time for various degrees of vertical confinement (Zeeuwen et al, 1983) 21

Figure 8: Summarized state of knowledge for predicting the rupture effects of pressure vessels as summed up by Baker (1984a) 36

Figure 9: Available data for non-dimensional analysis of fragment velocities and distance thrown (Baum, 1988) 40

Figure 10: Upper limit equation for missile 2-2 compared with experimental data (Baum, 1988) 40

Figure 11: Upper limit equation for missile 7-2 compared with experimental data (Baum, 1988) 41

Figure 12: Comparison of cumulative histograms of fragment ranges for LPG events where the vessels contained > 90 m^3 and LPG events where the vessels contained < 90 m^3 (Holden and Reeves, 1985) 42

Figure 13: General shape of a failure curve derived for a structural element from equation 16 (Scilly and High, 1986) 48

Figure 14: Summary of rupture configuration (Westin, 1971) 61

Figure 15: Comparison of data, from case studies and experimental studies, showing the distancedde fragments are hurled after catastrophic failure 63

Figure 16: Graph of the saturated vapour pressure curve and the superheat limit locus for propane (Jones, 1984) 69

NOMENCLATURE

List of Symbols Used in Equations

A_p = missile weight / projected frontal area (lb/ft^2)

α = momentum of release due to flash evaporation, per unit mass ($m\ s^{-1}$)

D_{max} = diameter of a sphere of equal projected area to fire ball at maximum size (m)

d = diameter of cylinder (m)

d_p = caliber of penetrator (diameter) (in)

E = kinetic energy of the projectile ($kg\ m^2\ s^{-2}$)

F = flashing factor

f_c = fraction of fuel burnt at end of combustion

g = gravitational constant

H = heat of combustion of fuel in fire ball

h = height (m)

h_p = thickness of steel plate that is just penetrated (in or m)

I = impulse

I_i = ideal impulse of zero duration required to produce a critical displacement

L = distance from fire ball centre (m)

ℓ = length of cylinder (m)

m = mass of liquid remaining after catastrophic failure (kg)

M = mass of fuel in fire ball (kg)

M_o = initial mass of liquid (kg)

M_p = mass of penetrator (lb)

M_R = mass of liquid released from containment (kg)

$\bar{M}$ = molecular weight of the flammable ($kg\ kmol^{-1}$)

m_v = mass of liquid flashing to vapour (kg)

N = length of rocket tub

n = increase in total number of moles per mole of flammable gas burnt stoichiometricly (mol)

P = peak load necessary for critical displacement

P_e = atmospheric (external) pressure (kPa)

P_i = step load

P_o = internal pressure of tank (kPa)

ΔP = pressure drop imposed (kPa)

Q = heat flux at distance L from fire ball centre (kW m^{-2})

R = radius of cylinder (m)

r = cloud radius (m)

R_s = distance structure is from explosion centre (m)

ρ_ℓ = liquid density (kg m^{-3})

ρ_v = vapour density (kg m^{-3})

ρ_A = density of air (kg m^{-3})

t = time from release (s)

t_d = duration of fire ball as an affective source of thermal radiation (s)

t_i = time from ignition (s)

t_w = thickness of concrete wall

T = thickness of concrete just penetrated (in)

T_c = isothermal temperature of fireball (K)

T_o = initial temperature (°C)

u = ultimate tensile strength of the target panel (Pa)

v = stoichiometric molar ratio of air to flammable gas

V = velocity of projectile (ft/s)

W = explosive yield equivalent to TNT (kg)

w = unsupported target panel span (m)

X = depth of penetration into infinitely thick concrete (in)

X_1 = depth of penetration into finite thick concrete (in)

ABBREVIATIONS

AAR	Association of American Railroads
BAM	German Federal Institute for Materials Research and Testing
BLEVE	boiling liquid expanding vapour explosion
CTC	Canadian Transport Commission
DOT	U.S. Department of Transport
FRA	Federal Railroad Administration
HSE	Health and Safety Executive
LPG	liquefied petroleum gas
P-I	pressure-impulse
PLG	Pressure Liquefied Gas
PRV	pressure relief valve
R-W	stand off distance-explosive yield
TC	Transport Canada
TDC	Transportation Development Centre
TDGD	Transport Dangerous Goods Directorate
UKAEA	Untied Kingdom Atomic Energy Authority

1-0 INTRODUCTION

1-1 Background:

This study was concerned with the state of knowledge of predicting the modes and effects of the failure of pressure liquefied gas (PLG) containers. PLG's are substances, such as propane and chlorine, that under atmospheric conditions are gases, but for transportation and storage are liquefied by pressurization. These containers hold a great deal of energy and an accident can result in an explosion. The most severe form of these explosions is called a boiling liquid expanding vapour explosion (BLEVE). PLG containers of specific interest to this study were rail tank cars, highway tank trucks and stationary storage vessels.

The number of accidents involving railroad tank cars carrying hazardous material in North America has shown a general decrease since 1979 (see figure 1). The number of fire induced ruptures fluctuated from 1971 to 1981 and since 1981 there have been very few (see figure 2). The work of the Association of American Railroad (AAR), the U.S. Department of Transport (DOT) and Transport Canada (TC) has shown success in reducing the number of serious accidents. Storage tank yards have also shown a good record in terms of accident occurrences but when accidents occur at these sites the results tend to be extreme. The accident in 1984 at Petroleo Mexicana's LPG storage and distribution centre in Mexico city is a good example of the severity (Pietersen, 1988).

Figure 1: Total Number of Accidents in Which There was a Release of Hazardous Materials (CTC Railway Transport Committee Operations Branch, 1986)

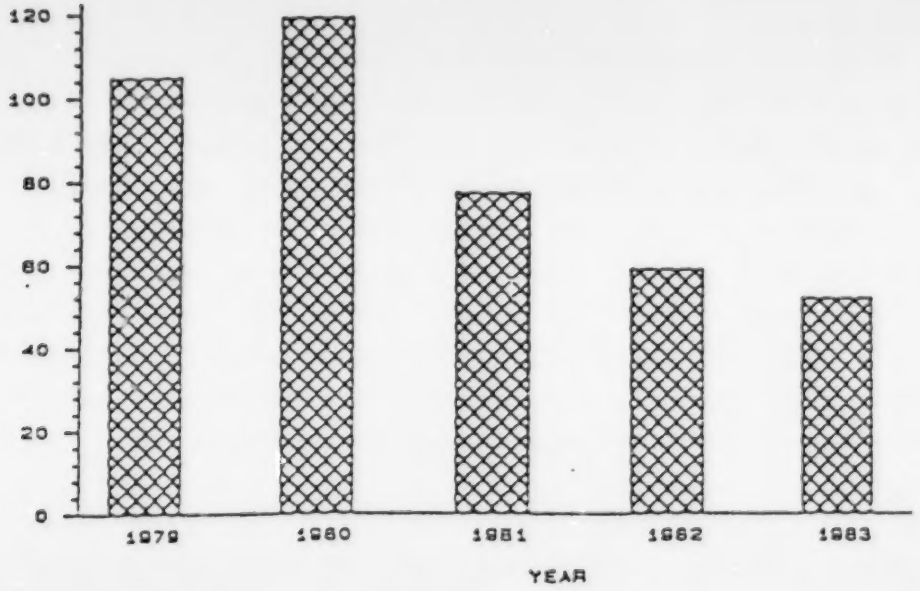


Figure 2: Fire Induced Ruptures of 112(114) Cars Before and After Retrofit Programs (Phillips, 1985)

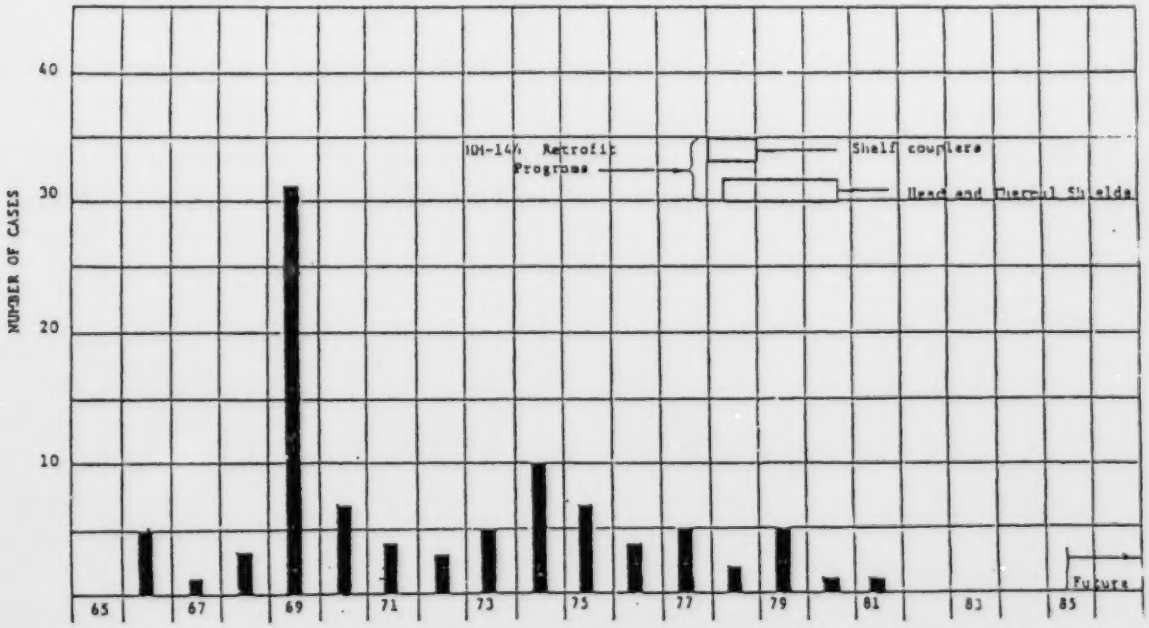


Figure 3 shows a chain of events from the beginning of an accident through to its effects. The work conducted by the AAR, FRA, DOT and TC has addressed the first part of this chain (the accident phase). Little is known about the next part of the event chain. What determines if a release causes a BLEVE or a boil off? What affects how severe the accompanying explosion is? In order to further reduce the risk of loss of life and property an understanding of the 'release phase' is required. This study is an assessment of the present knowledge of this phase.

Figure 3: Chain of events for a pressure liquefied gas container accident

Fire fighters need to know the projectile hazards and fire ball characteristics generated by the explosions of PLG containers in order to protect citizens and themselves. Storage facility designers need to know how to stop the spread of these events from container to container and minimize the damage to surrounding plant buildings and emergency water supplies. City planners need to know the projectile and the blast wave effects on private buildings so that new storage, loading or processing plants are located safely within cities.

1-2 Objective and Scope:

The objective of this study was to asses the 'state of the art' of knowledge relating to PLG container failure modes and the associated projectile and blast hazards. Specifically, we were interested in the effect of fill level on explosion severity, methods to identify conditions that promote the occurrence of BLEVE's and projectile formation and to identify the need for further research in these areas.

2-0 Literature Search

2-1 Overview and Sources of Information:

The main sources of information for this study have been reports, journal articles and conference papers found in the following data bases: Engineering Index, Applied Science and Technology Index, Transportation Research Board Publications Catalog and Highway Research Information Service Records. The computer data bases ComdexPlus and ISMEC were also used in the search.

The dangerous goods spills data base (administered by Transport Canada Transport Dangerous Goods Directorate (TDGD)) was found to be of little use for the purposes of this study. In order for the data base to be useful it must contain a detailed description of the accident and its effects including: the number, distance thrown and the mass of all fragments that were generated, the size and duration of the fire ball and the blast overpressure effects on any surrounding buildings or other structures. Accident data bases tend to catalog each type of accident and the losses of life and property. These would be useful for frequency of occurrence and cost severity studies but are of little use in understanding the effects of accidents in terms of missile generation, blast overpressure and fire ball characteristics.

2-2 Experimental Studies:

Experimental studies have been conducted in the following areas: 1) fire impingement of PLG vessels (rail tank cars and stationary storage tanks); and 2) laboratory tests of flashing of liquids to vapour and detonation of small and large scale fire balls.

In the early and mid seventies the AAR and the FRA in the U.S. conducted several full and 1/5 scale fire tests to investigate failure modes and the effectiveness of thermal insulation.

Throughout the eighties the West Germans, British and Canadians also conducted fire impingement tests. The British Health and Safety Executive (HSE) and the German Federal Institute for Materials Research and Testing (BAM) have both investigated water spraying systems for the protection of storage tanks. Canadians have conducted large scale fire tests to investigate the effects of novel explosion suppression devices and scaled fire tests to determine the effects of a burning relief valve flare on the heat flux to the tank and the fire. The University of New Brunswick in Canada has also conducted laboratory scale experiments to study the thermal hydraulics in PLG containers exposed to fires.

In the eighties the HSE and the University of Wisconsin have both conducted a limited series of flash evaporation experiments using freon in simulated vessel failures to help gain an appreciation of the mechanism of a BLEVE.

From the late seventies and through out the eighties the University de Poiters, the University de Bourges-Orleans, the Comissariat à l'Energie Atomique, the Electricité de France, Nederlanse Centrale Organisatie voor Toegepast - Natuurveterschappelijk Onderzoek (TNO) and Union Carbide have all conducted or collaborated on experiments to study vapour cloud explosions. These studies looked at the fire ball size, duration and intensity as well as the blast overpressures generated.

2-3 Modelling Studies:

Various Institutes have undertaken to further the understanding of the hazards associated with PLG storage and transportation through modeling. These models are based either on a theoretical estimation of the processes occurring and then validation of the derived relationship by experiments and/or case studies or by conducting experiments and analyzing the results non-dimensionally.

Fire impingement is a major cause of loss of containment for PLG vessels. Table 4 contains highlights of the early and recent work to predict the effects of fire on rail tank cars and similar vessels. The early work was conducted by the AAR and the FRA through The Railroad Tank Car Safety Research and Test Project and by the FRA on its own. Recently the Transportation Development Centre (TDC) of Transport Canada sponsored work to develop a computer program to model these effects. The British HSE conducted a review of the current computer models (Moodie, 1988) and the findings are summarized in Table 5.

One of the possible hazards from a release of a flammable PLG is a fire ball. Several institutions have sponsored the development of models to predict fire ball behavior. In the late seventies Ludwighafen/Rhein (in the Federal Republic of Germany) developed a model to predict the deflagration of flammable liquids after bursting of a pressurized tank. In the early eighties the HSE, the British Gas Corporation and the University of Aston have all developed models for predicting the duration, size and surface temperature of fire balls.

Another hazard from PLG container explosions is missile generation. Many models have been developed to predict the behaviour of these missiles. In 1971 Lockheed Propulsion Company developed a very basic model for the prediction of projectiles after an accidental explosion. It involved a sphere in a vacuum that burst into two halves. In 1972 the AAR and the FRA through the Railroad Tank Car Safety Research and Test Project developed a simple theoretical model of rocketing of tank car tubs. The Insurance Technical Bureau developed a model to predict the distance fragments from pressurized liquid tank ruptures were hurled. The Central Electric developed a model to predict the upper limit to the distance a projectile would be hurled. In the middle and late eighties Berkeley Nuclear Laboratories conducted experiments in the explosion of small scale pressurized gas vessels and pipes. They have developed several models based on

these studies to predict the distance fragments of various sizes would be thrown. At the same time the Southwest Research Institute also conducted a modelling review study as well as a large scale explosion test. In 1985 the British HSE conducted analysis of accident data to compare it to existing models to predict the fragment hazards from PLG vessel explosions. The Michigan Technological University in conjunction with the Southwest Research Institute, in 1988, studied and developed a model to predict the launch process of fragments.

Blast overpressure is another hazard that results from PLG vessel explosions. Work has been conducted to develop ways to predict blast damage to buildings and other structures. In 1978 the Southwest Research Institute developed a method to qualitatively predict the blast damage to structures from equivalent TNT yield explosions. The United Kingdom Atomic Energy Authority (UKAEA) has through out the eighties conducted research and development of prediction methods for the effects of blast loading and missile damage to metal and concrete structures. The Explosion and Flame Laboratory in Britain developed a model, based on scale experiments, to predict the blast deformation from vapour cloud explosions. The Polytechnic of the South Bank in Britain also conducted experiments on the blast deformation of cylinders in a vapour explosion.

2-4 Case Studies:

Two main sources of useful case studies come from the UKAEA (Holden, 1986) and the AAR (Westin, 1971). These are compilations of accident reports on major accidents involving the violent rupture of PLG vessels. They contain good information on the mode of failure and the number of and distance fragments were thrown. Case studies of individual accidents are few and far between in conference proceedings and journals and those that are often have been included in the large collection of accidents from the above

sources. Useful case studies not included in the two major collections or studies that are more specific have been reviewed as well. A couple of case studies not in the public domain have been provided by Transport Canada Transport Dangerous Goods Directorate.

2-5 Theory:

Universities, Fire fighters and Insurance agencies have all provided hypotheses to explain BLEVE's. All but one of these articles identify the same theory (the superheat limit theory, see section 3-4) as an explanation of the mechanism of a BLEVE. McDevitt et al (1987) identifies two additional theories (see section 3-4).

3-0 Discussion

3-1 Experimental Studies

3-1-1 Fire Impingement (see table 1)

In 1971 the AAR and the FRA joined together to form the Rail Tank Car Safety Research and Test Project. The objective of the work was to improve the safety of the transport of liquefied gases by rail. This agency conducted fire tests in 1973, and 1975.

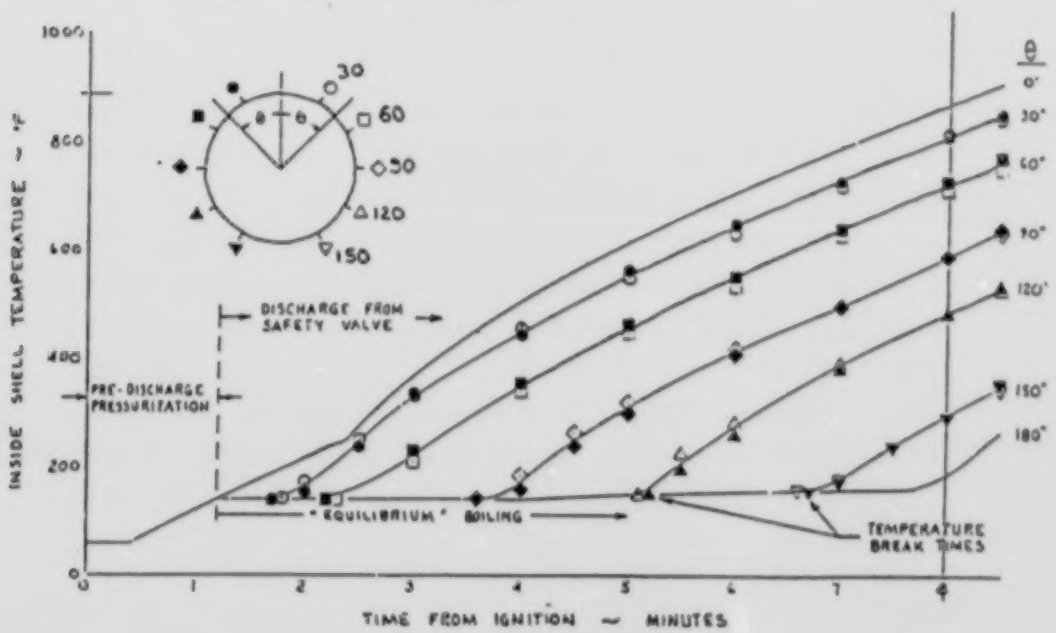
The first tests (Manda, 1973) involved 1/5 scale tanks and were designed to test a variety of insulation coatings and an experimental procedure. They discovered that the pressurization rates before the operation of the pressure relief valves (PRV's) could give a good indication of the heat flux to the lading. It was also shown that insulation was a good method of extending the life of pressurized vessels in a fire environment. After the 1/5 scale tests they moved on to conduct full scale tests.

In the full scale tests (Townsend et al, 1974) two tank cars, one insulated and one uninsulated, were subjected to fire engulfment. The experiments measured the internal pressure as well as the liquid, vapour and wall temperatures. Insulation significantly increased the survivability of the tank car (from 24 minutes for the uninsulated to 94 minutes for the insulated tank car). This study showed that the shell temperature of the wetted region of the tank remained at approximately the saturation temperature of the lading and the shell temperature next to the vapour space rose linearly with time.

The best representation of this tank wall temperature difference is shown in figure 4. This figure comes from the 1/5 scale tests (Manda, 1973) above. The test vessel had a

fill level of approximately 90% with 10 thermocouples placed at every 30. from the top excluding the top and bottom (positions 0. and 180., see figure 4). After about 1 minute the temperature of the tank shell has risen to the boiling point of propane. With boiling at the wall, the wall temperature will not rise much higher than the saturation temperature of the propane because the liquid propane is absorbing almost all the heat from the fire. At about 1min 45s the temperature of the thermocouple at position 30° began to rise linearly. Since the PRV was operating and the liquid was boiling off, the level of the lading has dropped. At this point the wall at the 30° position is no longer exposed to liquid but vapour. And since vapour conducts heat less readily than liquid the wall temperature begins to rise. Similar readings occurred at thermocouples positioned at 60° (2 min 15 s), 90° (3 min 30 s), 120° (5 min) and at 150° (6 min 45 s) as the lading level dropped.

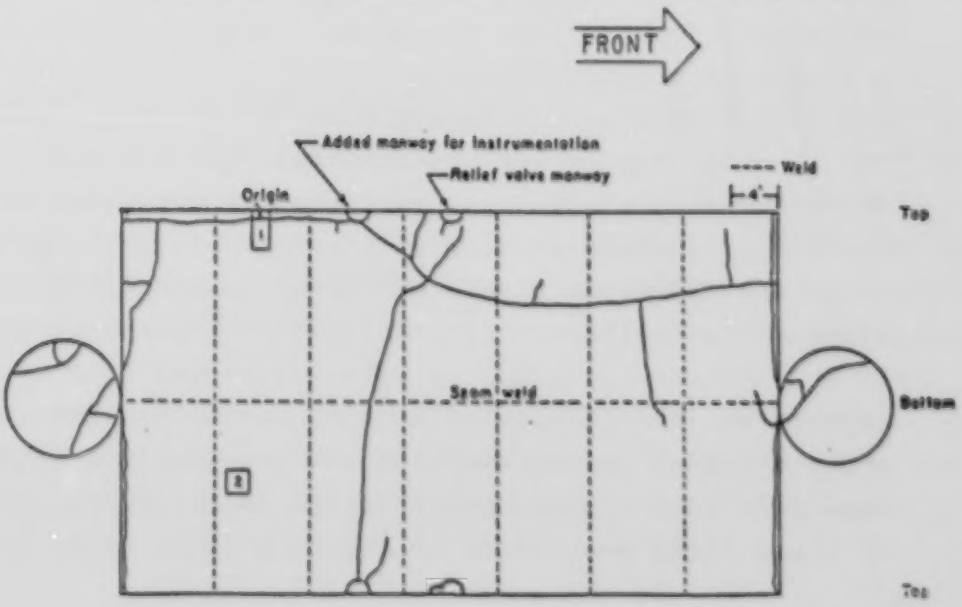
Figure 4: Wall temperatures for an uninsulated 1/5 scale test (Manda, 1973)



In Townsend's (1974) test both tank cars were allowed to rupture. The ruptures were well documented, the uninsulated car by Anderson and Norris (1974) and the insulated car by Early and Interrante (1975).

Anderson and Norris (1974) concluded that the rupture initiated as a stress rupture and propagated in an axial direction along the top of the tank before branching in the circumferential direction (see figure 5). The metallurgical analysis concluded that the longer a PLG tank is subjected to the high temperature of a fire the weaker the steel shell becomes. This weakening will lower the pressure the vessel can resist to a point even below the pressure relief valve (PRV) setting, which means that even if the PRV(s) are working properly the car may still rupture. Anderson and Norris also documented the distance thrown and the approximate mass of each of nine major fragments (the car fragmented into 65 pieces in total).

Figure 5: Shell Fracture Pattern For the Uninsulated Tank Car. Note the crack origin is in the axial direction and also that circumferential branches propagate from it some of which circled the tank and some of which did not. (Manda, 1974)



For the insulated tank car Early and Interrante (1975) documented the failure. The report concluded that the rupture was due thinning of the shell. They stated that the rupture originated in the axial direction along the top of the tank and when the explosion occurred it branched in a circumferential direction. The car ruptured into four major pieces, two of which were thrown out of the test pit and two of which remained in the pit. The mass of each fragment was not recorded but the approximate distance hurled was recorded.

Failure modes of PLG vessels have also been investigated by the BAM in the Federal Republic of Germany. Schulz-Forberg et al (1984) subjected three uninsulated LPG storage vessels to fire engulfment starting from different initial temperatures and pressures. Each tank contained a fill level of 50% and was allowed to rupture. They measured the pressure and temperature during the fire and the size of and distance thrown for each fragment resulting from the explosion. They discovered that the higher the initial temperature and pressure the shorter the time was to rupture. They also postulated that less fill would mean less time to rupture since more tank wall would be exposed to the vapour space. But Schulz-Forberg et al (1984) does not refer to any evidence to support this.

Tests into insulation performance in an engulfing fire environment have also been performed by the HSE (Roberts et al, 1983), (Moodie et al, 1985) and (Moodie et al, 1988). In these tests various sizes of tanks were tested with and without insulation.

Roberts et al (1983) conducted tests on stationary PLG storage tanks, one uninsulated and two insulated. The tanks used were 500L storage tanks filled to a level of 40%. None of these tanks were taken to rupture. When the temperature

and pressure measurements indicated failure was imminent the fire was quenched. Roberts et al stated that in most of the tests after 75 minutes the temperature difference between the wetted and unwetted region of the tanks were not different. They stated this indicated that there was a layer of vapour between the lading and the tank wall. This is the only test that comes to that conclusion; all other fire tests use the wall temperatures to indicate when the tank liquid level drops.

Moodie et al (1985) conducted fire tests on two 1/4 tonne and three 1 tonne storage tanks. In these tests they discovered that the wall temperature around the wetted part of the tank stayed at about the boiling point of the lading and the temperatures of the wall around the vapour space rose linearly with time. In all tests the PRV's failed near the end. One PRV on a 1/4 tonne tank failed closed, resulting in a rupture. The generated fragments were hurled a maximum of 120 m but most stayed within 20 m. The number of fragments was not reported. A metallurgical analysis revealed that the rupture began at the top of the tank along its axis before branching in circumferential directions. The other PRV's all failed safe (ie open) and allowed the tanks to vent safely and remain intact.

Moodie et al (1988) fire tested the same tank car five times with various fill levels (22, 36, 38, 58 and 72 percent). The tests were stopped when the temperature of the shell and internal pressure reached critical values. The PRV's were replaced for each test. Moodie et al state that since the time to reach critical internal conditions was shorter for lower fill levels the time to rupture is also shorter for lower fill levels. This is because with a lower fill level there is a larger portion of tank wall next to the vapour space where temperatures rise quickly.

The HSE (Billinge et al, 1986) and the BAM (Schoen and Droste, 1988) conducted tests to evaluate the use of water spraying systems (WSS) to protect PLG storage sites.

Billinge et al (1986) tested seven 1/4 tonne tanks protected by a WSS in engulfing fires. They found that the current British standards for spray rates were sufficient to prevent failure (one of their tests did fail but this was due to a PRV that did not open). The main conclusion was that water spraying systems reduce the flame temperature and will delay the time to first PRV opening prolonging the vessel's life.

Schoen and Droste (1988) conducted 10 fire engulfment tests on 4.85 m^3 LPG storage tanks protected by a conventional WSS and 5 on 4.85 m^3 tanks protected by a more efficient WSS. The tests were stopped when internal conditions approached rupture conditions. They concluded that the conventional WSS (with a water spray rate of 1000 $Lm^{-2}h^{-1}$) could not protect a tank from rupture while the improved WSS (with a water spray rate of only 400 $Lm^{-2}h^{-1}$) could prevent failure of a tank. They do point out, however, that thermal insulation would be sufficient to protect the tank from rupture alone and it is cheaper.

3-1-2 Flashing Liquid (see table 2)

Several institutes have sponsored research into the flashing of PLG's when they are suddenly depressurized. Bettis (1982) of the South Bank Polytechnic conducted small scale flashing liquid experiments using Freon 11. The experiments involved filling a spherical vessel, made up of two hemispheres held together pneumatically, with varying amounts of Freon 11 and then suddenly opening the vessel to depressurize the liquid. Measurements were taken of the expansion rates of the vapour cloud, the droplet size and pressure decay rate of the

pressure inside the vessel itself. He found that some of the PLG is released in two phase flow and some of the liquid remains in the vessel to boil off. He also found that the amount of liquid remaining in the vessel varied from 13% to 70% depending on the initial pressure and initial liquid fill level, although he does not specify what the relationship is.

The HSE sponsored Fletcher (1982) to research the phenomena of PLG flashing due to sudden depressurization. He used freon 11 and freon 114 as test fluids. These experiments involved heating a vessel containing the desired fill level of Freon to the desired superheat. Once the Freon was superheated a diaphragm on the vessel was opened to facilitate the depressurization which was video taped. The mass of the liquid remaining at the end of the experiment and the two phase flow of the discharge were measured. He found that the amount of liquid remaining in the vessel after depressurization was not a function of the initial fill level, but rather a function of the degree of superheat. Fletcher found that the freon must be superheated to at least 2 K to get flashing. He also provides the following expression (equation 1) to predict the mass of fluid remaining after release and the density of the two phase release.

$$\frac{m}{M_o} = \left[\frac{m_v}{M_o} \frac{\rho_\ell}{\rho_v} + \left(1 - \frac{m_v}{M_o} \right) \right]^{-1} \qquad (1)$$

$\frac{m_v}{M_o}$ is the theoretical flash which can be evaluated from the physical properties and the initial conditions of the liquid, although Fletcher does not say how

Sergent and Lundy Engineers, General Electric and The University of Wisconsin collaborated to investigate liquid

flashing (Peterson et al, 1984). These experiments involved the flashing of liquid at room temperature from pressures of 11.4 to 27.0 kPa gauge. The flashing was observed by high speed photography and the mass transfer rates were measured. They found that for low pressure drops only evaporation occurs and mass transfer rates for flashing are 10 to 12 times faster than for evaporation. When flashing occurs it is more violent at the surface, causing a heterogeneous temperature profile. Peterson et al derived an equation for a flashing factor (F) defined as the ratio of the mass transfer found in flashing to the mass transfer from evaporation. The higher the value of F the more violent the flashing.

$$F = 27.5 - 0.527T_o - 0.129\Delta P \qquad (2)$$

3-1-3 Fire Ball and Blast Overpressure (see table 3)

At the end of the seventies Union Carbide conducted research into the energy release of high pressure vessels (Pohto, 1979). The small scale experiments involved blowing up 7 models of an actual PLG vessel being used in a chemical process (each with a different wall thickness). Using air to fragment each model the blast overpressures and the velocities of each fragment were measured for each explosion. The pressures needed to rupture the spheres were 103, 206 and 345 MPa. The vessels were contained in a five sided cement cube to simulate the containment walls around the real pressure vessel. All of the vessels failed in only two pieces and the average peak missile velocity was 115 m/s. The report presents a graphical representation of each blast based on the internal pressure (overpressure vs distance from centre).

The TNO conducted small, medium and large scale blast overpressure tests. The small and medium scale tests by Van Wingerden and Zeeuwen (1980) and the large scale tests by Zeeuwen et al (1983).

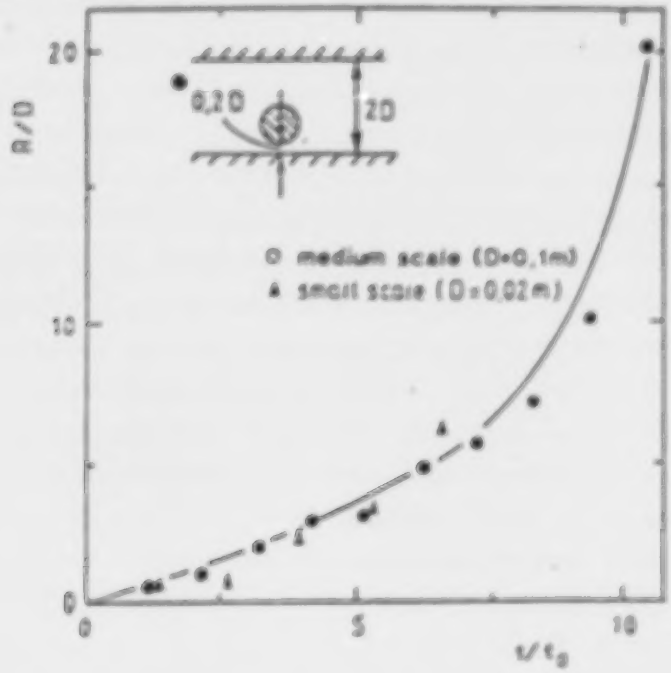
Van Wingerden and Zeeuwen (1980) conducted small and medium scale tests to determine the effects of obstacles in the vicinity of the vapour cloud on the severity of the explosion. They ignited a vapour cloud over a test platform made up of a steel plate base covered by horizontal cylinders supporting a perforated steel plate cover. The experiment measured the blast overpressures as they propagated out from the test site. The diameter of the cylinders, the spacing of the cylinders and the presence of the perforated steel plate cover were varied. These experiments showed that the blast effects were greatest when the spacing between the cylinders was 0.2 diameters and that the blast effects did not change appreciably for separations of over 2 diameters. Van Wingerden and Zeeuwen state that the similarity between the small and medium scale test results indicate that predictions based on these tests will be valid for large scale cases as well (see figure 6 for a comparison of small and medium scale results).

Figure 6: Simple scaling of vapour cloud explosion experiments for partially confining obstacles. (Van Wingerden and Zeeuwen 1980)

H = 2D
P = 2.25D
R = flame radius
h = 0.2D

7 - 8% ethylene-air mixture

$t_0 = \frac{D}{2v_i}$, v_i -is initial flame speed



Large scale tests were then conducted. Twenty eight vapour clouds were ignited to determine the effects of obstacles on the blast wave by J.P. Zeeuwen et al (1983). The tests consisted of igniting a 1000 kg vapour cloud of propane on test sites which had either open space, vertical uncovered short pipes, vertical short pipes covered with steel plates or uncovered horizontal pipes. The flame speed and the blast overpressures were measured at various distances from the blast site. Zeeuwen et al state that the tests indicated that in an open site or a site with uncovered vertical obstacles produced no large flame accelerations and the smallest blast effects. The blast pressures produced from detonation in a site with uncovered horizontal obstacles was larger than those of both the open site and the site with

uncovered vertical obstacles. The covered vertical obstacles produced the largest blast effects (as high as 1000 kPa) and inside the obstacles there was constant flame acceleration producing large flame speeds. The high flame speeds produced by confinement drop dramatically when the flames enter the open. See figure 7 below for a graphical representation of the speed drop after leaving the covered portion of the array.

Figure 7: Flame distance from source against time for various degrees of covered vertical confinement (Zeeuwen et al, 1983)

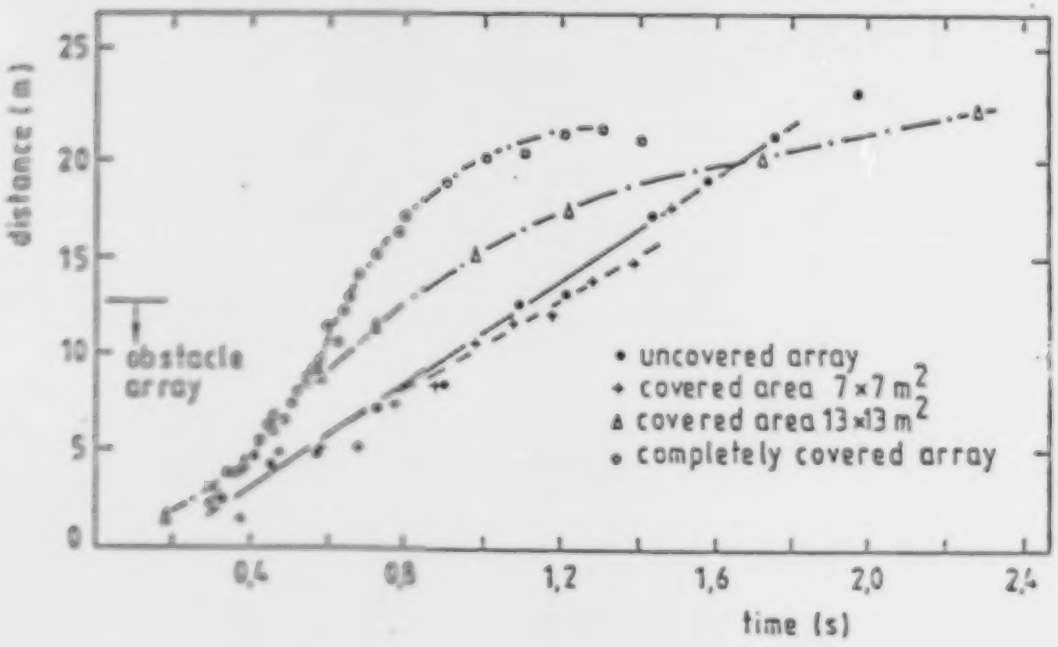


Table 1: Fire Impingement Tests

Title / Date	Author(s)	Sponsor	Focus	Findings	Recommended Further Work	Comments
Phase II Report on Analysis of 1/5 scale Fire Tests 1973	L. J. Mende	Association of American Railroads	- 7 1/5 scale fire tests were conducted to evaluate test procedures and thermal shielding	- pressurization rates before discharge of PRV can provide an indication of the effective heat flux to the lading - any of the insulation systems tested can reduce the unit heat flux by a factor of 5 or 6 for durations of longer than 40min	- no recommendations	- 2 tests were conducted with water to evaluate test procedures - 2 tests were conducted on uninsulated tanks - 3 tests were conducted on tanks insulated with 3 different types of insulation - suggested that test results should not be extrapolated to full scale - water tests gave no useful data
Comparison of Thermally Coated and Uninsulated Rail Tank Cars Filled With LPG Subjected to a Fire Environment 1974	W. Townsend C. Anderson J. Zook G. Cowgill	Federal Railroad Administration	- fire test of two tank cars (insulated and uninsulated)	- the rate of temperature increase in the insulated car was lower than for the uninsulated car - the rate of vapourization in the insulated car was lower than for the uninsulated car - insulated car will survive longer	- no recommendations	- has mass and distance information for the major fragments - lower temperature means higher rupture pressure and lower vapourization rate means a lower pressure
Fragmentation and Metallurgical Analysis of Tank Car RAX 201 1974	C. Anderson E.B. Morris	Federal Railroad Administration	- analysis of the rupture of an uninsulated tank car	- the longer the tank car is subjected to high temperatures the lower the pressure that is required to rupture the vessel - failure due to stress rupture - failure initiated in an axial direction	- no recommendation	- failure occurred at an area where a thermocouple was mounted (tests showed failure was imminent) - car ruptured after 24.9min
A Metallurgical Investigation of a Full-Scale Insulated Rail Tank Car Filled With LPG Subjected to A Fire Environment 1975	J.C. Early C.C. Interrante	Federal Railroad Administration	- analysis of the fragments of an insulated tank car after rupture due to fire	- rupture initiated in an axial direction due to thinning then the explosion occurred and the crack propagated circumferentially	- no recommendations	- tank car was approx 100% full - tank failed after 94min - tank ruptured into 4 major fragments - two ejected from pit two remained in pit

Table 1: continued

Title / Date	Author(s)	Sponsor	Focus	Findings	Recommended Further Work	Comments
Testing and Evaluation of the Explosafe System as a Method of Controlling the BLEVE 1980	R.D. Appleyard	Transportation Development Centre	- outlines the investigation of the effectiveness of Explosafe in preventing the failure of pressure vessels	- two systems using Explosafe of the three tested were successful in preventing rupture of a pressure liquefied vessel engulfed in flames	- full scale tests should be conducted	- tests were conducted on a 1/5 scale - 2 tests of unprotected tanks and 4 tests with 3 different setups of explosafe - both unprotected tanks ruptured and no protected tanks ruptured although one system of explosafe was close to failure - tanks filled to 85% - one unprotected tank failed after 9.5min, - the other after 8min - neither rupture generated fragments
Fire Engulfment With LPG Tanks With a Range of Fire Protection Methods 1983	A.F. Roberts D.P. Cutler E. Billinge	Health and Safety Executive	- fire test of 1 uninsulated & 2 insulated storage vessel	- after 75min in the majority of the tests the temperature difference between upper and lower wall was small indicating that the propane was not wetting the lower wall but was supported by a vapour layer	- no recommendations	- calibration trials using water showed that the fire conditions could be reproduced - tanks not taken to rupture
Experimental Determination of the Heat Transfer in the Vapour Space of a Partially Filled Horizontal Cylinder 1984	G. Qureshi	Transportation Development Centre	- model of effects on vapour space of fire engulfment	- an open pressure relief value enhances the heat transfer from the wall to the vapour	- no recommendations	
Failure Mechanisms of Propane Tanks Under Thermal Stresses Including Fire Engulfment 1984	D. Schulz-Forberg H. Droste H. Charlett	Federal Institute for Materials Research and Testing (BAM)	- fire test of 3 LPG storage vessels - the initial temperature and pressure were varied	- the higher the initial temperature and pressure the shorter the time to rupture	- Further tests and theoretical work needed	- postulates that less fill will mean less time to rupture - test conducted with 50% fill on uninsulated storage vessels
An Experimental Investigation of a Cylindrical Vessel Engulfed in Fire With a Burning Relief Valve Flare Present 1985	A.M. Birk	Transportation Development Centre	- tests of a cylindrical vessel exposed to fire engulfment plus a PRV flare and only a PRV flare were conducted	- heat flux from a flare alone are small, 3 - 6% compared to the heat flux due to fire engulfment - the effect of a flare to an already engulfing fire is negligible in its effects on the tank - the flare effects the pool fire geometry and so may increase the radiant heat to remote objects	- no recommendations	- tests conducted indoors - flare only test consisted of water as loading and 6.5min flare burn - flare 6 to 7m long - flare and engulfment tests consisted of water as loading a pool fire of JP4 jet fuel (for 14.5min) with 2 flare burnings of 3 and 2min

Table 1: continued

Title / Date	Author(s)	Sponsor	Focus	Findings	Recommended Further Work	Comments
The Fire Engulfment of LPG Storage Tanks 1983	E. Moodie K. Billings D.P. Cutler	Health and Safety Executive	- fire tests of two uninsulated 1/4 tonne and three 1 tonne tanks - to measure temperature, pressure and PRV discharge rates	- temperature of walls adjacent to vapour space rose linearly - temperature of wall adjacent to liquid space rose to a plateau (boiling point) then rose further (when the liquid level dropped) - rupture of one 1/4 tonne tank was axial - pressure relief valves failed open near the end of the tests and may have prevented the failure of the other tanks	- require further information on the boiling behavior of the liquid - require further information on the quality and mass flow rates of the propane as it is discharged through the PRV	- all PRV's failed due to fire damage to the valve seats and springs - 1/4 tonne tests conducted at 40% fill - pieces from the 1/4 tonne test that failed were buried up to 120m but most only 20m - 1 tonne tests were conducted at 20%, 40% and 80% fill levels
Tank Car Thermal Response Analysis: Executive Summary: Volume 1 1985	J.E.S. Venart	Transportation Development Centre	- report summarizes the work done to date with Expandafo	- internal pressure for the testing is determined by liquid surface temperature and low boiling point impurities - 25mm and 50mm thick Expandafo layers showed little or no advantage	- work is needed to determine the effects of PRV operation, heat flux, loding fill and orifice diameter on pressure relief and thermal hydraulics - use of high heat flux interior surfaces for internal vapour space cooling	- lab simulations of fire conditions conducted with and without Expandafo varying heat flux, PRV orifice diameter and fill level - conducted studies of the stratification and boundary layers of the fluid in a cylinder heated with and without Expandafo - boiling and liquid swelling was considered with and without Expandafo
The Use of Water Sprays To Protect Fire Engulfed LPG Storage Tanks 1984	K. Billings E. Moodie M. Bechtel	Health and Safety Executive	- series of 7 tests on 1/4 tonne tanks engulfed in fire protected by a water spray system	- currently recommended spray rates are sufficient to prevent failure - PRV opened after spraying began (1 - 3min) - temperature of vapour space walls rose linearly - temperature of liquid space walls rose to a plateau then when liquid level dropped from PRV operation the temperature rose linearly - water spray reduced flame temperature and lengthened time to PRV opening - PRV discharge rate larger for water protected tank than for unprotected (lower temperature) - insulation is more effective than water sprays	- no recommendations	- tanks at 40% fill - PRV's on lowest water rates failed safe (ie open) because of burnt valve seats - tests with higher water spray rates the PRV's operated correctly - seventh test vessel failure occurred (non catastrophic)

Table 1: continued

Title / Date	Author(s)	Sponsor	Focus	Findings	Recommended Further Work	Comments
Investigation of Water Spraying Systems For LPG Storage Tanks by Full Scale Fire Tests 1988	W. Schoen D. Droste	Federal Institute for Materials Research and Testing (BAM), Berlin	- reports on 10 fire tests on 4.85^3 LPG storage tanks protected by a conventional WSS - and 5 protected with a modified WSS	- conventional WSS with 1000Lm^-2h^-1 could not have protected the tank against rupture - improved WSS with 400Lm^-3h^-1 could protect the tank against rupture - some thermal insulation or other protective measure needs to be added to the conventional WSS for it to be effective - improved WSS can survive a fire for over 90min	no recommendations	- used 20% fill for the conventional WSS tests - used 20% and 80% fill for the improved WSS tests - tanks not taken to rupture - thermal insulation alone is enough to protect the tank for 90min
Fire Engulfment Tests on a 5 Tonne LPG Tank 1988	K. Moodie L. T. Cowley R. B. Denny L. M. Small I. Williams	Health and Safety Executive and Shell Research	- fire test of 1 uninsulated tank car 5 times	- time to rupture is shorter for lower fill levels	- no recommendations	- tank not taken to rupture - same car used each time

Table 2: Flashing Liquid Experiments

Title / Date	Author(s)	Sponsor	Focus	Findings	Recommended Further Work	Comments
Two Phase Flashing Releases Following Rapid Depressurisation due to Vessel Failure 1982	R.J. Bettis	Health and Safety Executive and South Bank Polytechnic	- small scale flashing of superheated liquids due to the failure of pressure vessels has been studied using Freon 11	- amount of liquid remaining varies (from 70% to 13%) with initial pressure and the amount of material initially present - provides a preliminary model for the release of liquid and two phase flow from vessel failure - a model was developed for the pressure vs time characteristics - some of the liquid is released as droplets some as vapour and some remains in the vessel	- no recommendations	- experiments studied the expansion rates and droplet size of the two phase flow and the effect of the initial conditions - the decay of pressure in the vessel was also studied - "rupture" of the vessel was simulated by pneumaticly opening the vessel - previous models assumed instant failure and no interaction between two phase flow and the vessel
Sudden Discharge of a Superheated Fluid To Atmosphere 1982	B. Fletcher	Health and Safety Executive	- experiments were carried out using Freon 11 and 114 to help understand the flashing of liquids and how much of the contents of a vessel flashed	- amount of liquid remaining is not a function of initial fill level - a superheat of at least 2·K is required	- no recommendations	- vessel was filled with F11 or F114 and heated to the desired superheat then a diaphragm was burst and the amount of liquid remaining was measured - the discharge was also recorded by video camera - provides a model to predict the mass of fluid remaining in the tank after flash, the density of the mixture of liquid and vapour produced
Investigations of Liquid Flashing and Evapouration due to Sudden Depressurization 1984	R.J. Peterson S.S. Grewal M.M. El-Wakil	Sargent and Lundy Engineers, General Electric and U of Wisconsin	- the flashing of Freon 11 at room temperature is investigated for depressurization from 11.4 to 27.0kPa gauge pressure to atmospheric	- at low pressure drops only evapouration occurs but at higher ones flashing occurs - mass transfer rates for flashing are 10 to 12 times faster than for evaporation alone - when flashing occurs it is more violent at the surface this causes a heterogeneous temperature profile composed of superheated, saturated and subcooled liquid	- no recommendations	- flashing was observed by high speed photography and mass transfer rates were measured - equations to relate the mass transfer rates from flashing to the mass transfer rates due to evaporation alone are derived

Table 3: Fire Ball and Blast Overpressure Experiments

Title / Date	Author(s)	Sponsor	Focus	Findings	Recommended Further Work	Comments
Energy Release From Rupturing High Pressure Vessels: A Possible Code consideration 1979	H.A. Pohto	Union Carbide	- reports on seven tests conducted to establish energy release from pressurized gas spheres with varying wall thickness	- graphical representations for the overpressures from each blast with a specific internal pressure are provided - average fragment velocity was 115m/s - all vessels failed in only two pieces	- further explosion work needed in order to help establish a design code	- calculated fragment velocity - spheres enclosed in concrete box open at one end - blast overpressure measured - burst various wall thicknesses at 103, 206 and 345MPa
Vapour Cloud Explosion Experiments For Use in Hazard Assessment 1980	C.J.H. Van Wingerden J.P. Zeeuwen	TNO	- provides an insight into the effects of obstacles on the blast from vapour clouds	- without an upper confinement a spacing of 0.2D between the base plate and the tubes produced the maximum blast effect, spacings of larger or smaller reduced the effects - with a spacing of 2 to 4.5D between each tube the blast effect did not change much - minimal differences in the small and medium scales show that these experiments are applicable to a realistic storage site	- the blast effects inside the obstacles need to be measured since these will effect the other storage cylinders	- experiments performed on small and medium scales to measure the effects on external blast due to obstacles - tests consisted of igniting a vapour cloud inside a steel a plate covered by horizontal tubes which were then covered by a perforated steel plate or left open - the size and spacing of the tubes was varied
Experimental Analysis of Unconfined Explosions of Air Hydrocarbon Mixtures: Characterization of the pressure field 1983	J. Brossard J.C. Leyer D. Desbordes J.L. Garnier J. Hendricks J. Perrot J.P. Saint-Cloud	U de Bourges-Orleans, U de Poitiers, Coelssarlat l'Energie Atomique and Electricit de France	- discusses the results of explosion tests of vapour clouds conducted to help design nuclear plants to be safe from hazardous chemical accidents	- in real accidents only deflagration would occur since perfect conditions need to be met for detonation - for a hemispherical cloud a mass equivalent of 1kg of hydrocarbon to 4kg of TNT exists - flame speed and blast pressure depend on concentration of gas - flame speed and blast pressure also depend on stratification - there is no exact similarity between the pressure field of a hydrocarbon mixture and TNT	- no recommendations	- acetylene, ethylene and propane air mixtures were tested - flames may propagate by either deflagration of detonation - normally deflagration occurs causing a spherical flame front to travel out from the ignition source producing a blast wave - for 6.5% and 9% ethylene max speeds were 11 to 16m/s with 300 to 500kPa overpressure

Table 3: continued

Title / Date	Author(s)	Sponsor	Focus	Findings	Recommended Further Work	Comments
Experimental Investigations Into Blast Effects Produced By Unconfined Vapour Cloud Explosions 1983	J.P. Zeeuwen C.J.H. Van Wigerden D.M. Dawe	TNO	- investigated the blast effects of vapour explosions through releasing and igniting 1000kg of propane gas in an area with and with out obstacles (28 tests)	- in an open site or a site with uncovered vertical obstacles no flame acceleration occurs - high flame speeds produced by confinement drop drastically when flame enters an open space - covered vertical obstacles produce a constant flame acceleration and large blast effects - uncovered horizontal obstacles produced greater blast effects than uncovered vertical obstacles	- no recommendations	- test obstacles included horizontal pipes and vertical large diameter short pipes - tests measured the distance that flame propagated, flame speed and overpressures
Experimental Study of the Overpressures Generated by the Detonation of Spherical Air Hydrocarbon Gaseous Mixtures 1986	J. Brossard J. Duco T. Gobert A. Lannoy J. Perrot	U de Poitiers, Comissariat l'Energie Atomique, Electricit de France and Center d'Etudes Scientifiques et Techniques d'Aquitaine	- ignited spheres of air hydrocarbon mixtures and measured blast overpressure	- blast effects for rich ethylene and acetylene at ambient conditions are dependent on radius of the cloud and volume of the cloud not on the gas in the cloud - equations derived should be reliable up to several hundred m^3	- effects of explosion hight above ground need to be carried out - larger clouds need to be detonated to see if scaling effects exist	- volume of spheres ranged from 1 to 54m^3 - used 16% acetylene and 8% ethylene air mixtures - flame speed was about 1900m/s - empirical relations were derived to predict blast overpressures with volume and dimensionless radius (distance / cloud radius) as parameters - over pressures can be as high as 1000kPa

3-2 Modelling Studies

3-2-1 Thermal Modelling (see tables 4 and 5)

Table 4 contains highlights of early and recent thermal model development work.

The earliest attempts at modelling the effects of fire on PLG tanks was made by the AAR and the FRA. Manda (1971) conducted a theoretical evaluation of the effects of fire on a rail tank car. This work came to two conclusions that were later shown to be incorrect. A tank car's survivability would be better if the PRV's setting were higher and the liquid fill level was as high as possible. Since PLG tanks fail a pressures lower that PRV settings in a fire environment raising the setting would not prevent failure. The suggestion of liquid fill level fails to account for liquid swelling which produces large pressure on a totally filled tank. This study did however inspire the tank car engulfment tests the AAR and the FRA carried out (see section 3-1-1) and further model development.

Graves (1973) developed a computer model of a rail tank car engulfed in flames as a preliminary step to the fire tests of 1975 suggested by Manda (1971). This program was a preliminary attempt to model thermal effects on tank cars. Graves points out that his program has many short comings. This program was the first in a series of computer programs to model thermal effects on PLG tanks. Table 5 is a chronological list of computer models currently available for modeling thermal effects on PLG containers. Table 5 was found in Moodie (1988) and revised by the authors to follow chronological order.

The most recent work in this area has been done at the University of New Brunswick. Audemir et al (1988) developed a computer model (see Venart and Sousa on table 5) which has

shown good agreement with tests. This testing and modelling program is being sponsored by TDC and is on going.

Moodie (1988) as well as Crocker and Napier (1989) have both published overviews of thermal modelling techniques. Moodie (1988) has determined from these models and supporting experiments that the smaller the tank and the lower the fill level the shorter the time to rupture.

3-2-2 Fire Ball Modelling (see table 6)

The HSE, Ludwighafen/Rhein in West Germany, the British Gas Corporation and the University of Aston have all sponsored the development of fire ball models.

Maurer et al (1978) developed a model to predict fire ball characteristics. The model provides equations to predict fire ball size, duration, the blast overpressure generated and vapour cloud mixing. The model was based on six small scale tests using propylene. They concluded that this model could be scaled to predict full scale fire ball proprieties.

Roberts (1982) of the HSE surveyed previous work and compared modelling techniques. He outlines two models and recommends one. To predict fire ball radius he recommends equation 3. For predicting maximum fire ball diameter he recommends equation 4. For the duration of a fire ball he recommends equation 5. To predict the the heat flux from a fire ball he recommends equation 6. Roberts (1982) discusses the effects of initial momentum from flash evaporation and the initial state of the liquid on cloud and fire ball formation. He concluded that the maximum diameter of a fire ball is not dependent on fuel type. He also found that the vapour pressure at the time of failure will effect the portion of gas released into the fire ball, the rate of combustion, the

probability of a vapour cloud explosion and the thermal radiation output.

Equation 3 is Roberts recommended equation for fire ball radius. The symbol 'α' refers to the momentum of release per unit mass (for propane has the value 120 m/s for a vapour pressure of 0.5 MPa and 220 m/s for 1.0M Pa). The maximum size of a fire ball is given by equation 4. This equation gives the diameter of the equivalent sphere based on the projected area of the real fire ball. It is insensitive to the fuel type or the mechanism of cloud formation. Equation 6 gives the heat flux at a given distance from a fire ball. The variable 'f' is the fraction of heat release due to combustion that is radiated from a fireball and it is estimated to be 0.3 for a system failing at 1.5 MPa and 0.4 for a system failing at 5 MPa. The variable 'a' is a atmospheric transmission coefficient to account for attenuation effects by the atmosphere and its value depends upon the atmospheric conditions (humidity etc). Typical values for 'a' are 0.75 at 50 m and 0.61 at 500 m.

$$r = \left(\frac{4 \alpha M_R t}{\Pi \rho} \right) \tag{3}$$

$$D_{max} = 5.8 M^{1/3} \quad \text{for above ground fire balls} \tag{4a}$$

$$D_{max} = 7.3 M^{1/3} \quad \text{for ground fire balls (hemispherical)} \tag{4b}$$

$$t_d = 0.45 M^{1/3} \tag{5}$$

$$Q = \frac{f H M}{4 \Pi L^2 t_d} a \tag{6}$$

Moorhouse and Pritchard (1982) also reviewed previous work for the British Gas Corporation. The Moorhouse and Pritchard (1982) recommended equations for predicting fire ball

characteristics are different than those of Roberts. Equation 7 is to predict the maximum diameter of a fire ball. Equation 8 is Moorhouse and Pritchard's recommended equation for the effective duration of a fire ball.

$$D_{max} = 5.33\ M^{0.327} \tag{7}$$

$$t_d = 0.923\ M^{0.303} \tag{8}$$

Libou and Maund (1982) conducted some small scale fire ball experiments and reviewed previous data. From their work they derived equations to predict the characteristics of fire balls. The equation for the duration of a fire ball is given by equation 9. The equivalent spherical, which is dependent on fuel type, diameter at the completion of combustion can be calculated with equation 10. Equation 11 gives an expression for the height a fire ball rises over time. They also provide a model to predict the hazards of a BLEVE fire ball on people (this is a complex iterative method, readers are urged to see the original article). They discovered that the surface temperatures of a fire ball from butane is 1300 K and is 1500 K for methane. They also concluded the spherical diameter of a fire ball increases at a constant rate through out combustion.

$$t_d = 0.45\ M^{1/3} \tag{9}$$

Generally

$$D_{max} = 0.539\left(e + \left(n + 1\right)f_c\right)^{1/3}\left(T_c\,\frac{M}{R}\right)^{1/3} \tag{10a}$$

For Methane

$$D_{max} = 5.92\ M^{1/3} \tag{10b}$$

For Butane

$$D_{max} = 6.95\ M^{1/3} \tag{10c}$$

$$h = 10t_i \qquad (11)$$

3-2-3 Projectile Modelling (see table 7)

Much effort has been put into developing models to predict the behaviour of projectiles generated from pressurized container failure. Most of this work has been in developing models for projectiles from pressurized gas vessel explosions. Work has been sponsored by Lockheed Propulsion Company, the AAR, the Insurance Technical Bureau, Central Electric, the UKAEA, the Michigan Technological University, Southwest Research Institute and Berkeley Nuclear Laboratories.

It should be noted that the relevance of modelling projectiles formed from pressurized gas container explosions to the modelling of projectiles formed from PLG vessel explosions is not known. Only W.E. Baker and M.R. Baum discuss a difference.

Baker (1984a) and Baum (1988) both separate the fragments from the rupture of pressurized gas vessels and the fragments from the rupture of PLG vessels (see the paragraphs below for more details). The work in modelling the projectiles generated from pressurized gas vessel failure is included in this report for two reasons. It may be useful if experimental evidence shows that there is no difference in the behaviour of fragments from these two types of contained fluid. Also, even if there is no similarity in behaviour, the pressurized gas modelling work could serve as a guide for developing a model to predict the behaviour of fragments formed from PLG containers.

Prause et al (1972) analyzed tub rocketing from tank cars involved in accidents. They determined that the distance

travelled by a tub is governed by the following parameters: the temperature and pressure of the lading, the length of the tub, the launch angle and the outage of the tank at the time of rupture. They also found that the diameter of the tank and the lading type were not factors. They developed a model based on these observations and with it they concluded that the longest distance that tubs (formed from propane carrying rail tank cars) could be rocketed is between 1220 m and 3350 m. It is based on isentropic expansion of the lading with 100% of the energy released going into the rocketing effect. Their model predicts that the range of projection is affected by the level of lading in the tank. As the level of the lading becomes lower the range of rocketing drops quickly. Prause et al (1972) also speculate that long tubs will be more likely than short tubs to be launched along the tank axis and travel straight. This model is hard to validate since accurate information on lading level, launch angle, etc. are hard to find in accident reports. It should be considered as giving conservative results since it assumes totally efficient energy conversion from the fluid to the fragments.

Munday (1980) derived a model for predicting projectile hazards of ruptures based on knowing fragment shape, drag coefficient and lift. He states that stored energy methods are not a good indication of the distances fragments are hurled since they make the assumption that the most important thing to the range of fragments is the amount of energy supplied to them from the expanding fluid. In fact, he says, there is another important factor that determines the distance travelled, the fragment's shape. His model is based upon knowing the "shape" of fragments (the important properties are lift and drag) that are formed. Since his model is based upon knowing the shape of the generated fragments he says that no attempt to present his model in terms of a graph would be appropriate since the model should

be used to analyze individual cases. This model is not validated since it requires very specific data that is not normally taken from accident scenes or even experiments.

Talacz and Smith (1980) have classified missiles into three different types. Type (a) & (b) are shrapnel type missiles, (a) is classified as a flat approximately round section of the vessel expelled, (b) is a valve from the vessel that is expelled. Type (c) is classified as a rocket type missile. They review the methods for predicting the velocity and distance hurled for missiles of type (a) & (b) and provide a model that they feel is acceptable to give an upper limit to the distance a missile will be projected. This model has been validated from their own experiments on pressurized gas containers. They did not conduct experiments into the characteristics of the type (c) missiles and their review discovered that there was no validated model for rocket type missiles. This paper also contains models to predict penetration and scabbing caused by missiles to concrete barriers and equations to relate the effects of naturally shaped missiles to the effects of cylindrically shaped missiles commonly used in experimentation.

W.E. Baker of the Southwest Research Institute has contributed to the understanding of the blast effects of explosions. In the area of catastrophic pressure vessel failure he has conducted experiments and reviewed other's modeling work.

In preparation for a pressurized gas explosion test Baker (1984a) conducted and reported on a survey of prediction methods for the fragment hazards associated with all types of pressure vessels. In this paper he outlines the state of the art at predicting fragment characteristics of bursting pressure vessels. This article is the first to suggest that there is a difference between the fragment hazards of

pressurized gas vessels and PLG vessels. He describes the state of knowledge at predicting fragment characteristics from PLG vessels as poor to fair (see figure 8). He does not report any validated models for predicting projectile hazards from PLG vessel failure. In this article Baker presents a graph to predict the maximum fragment range for gas pressurized vessel ruptures and the blast overpressure.

Figure 8: Summarized state of knowledge for predicting the effects of rupture of pressure vessels as summed up by Baker (1984a)

Physical State of Pressurized Fluid	Characteristic	State of Knowledge
Gas	Blast wave properties	Excellent for spherical vessels burst into many fragments, good for spherical vessels split in half, poor in close proximity to cylindrical vessels.
	Fragment velocities	Good, for all geometries
	Fragment mass distributions	Poor
Flash-evaporating fluid	Blast wave properties	Fair
	Fragment velocities	Poor
	Fragment mass distributions	Fair
Compressed liquid	Blast wave properties	Poor, but hazard is low
	Fragment velocities	Zero, and hazard may not be low
	Fragment mass distributions	Zero, and hazard may not be low

A test was then conducted on a full size pressurized gas cylinder by Baker (1984b). In the test a pressure vessel was ruptured pneumaticly and the predicted fragmentation was compared to the actual fragmentation. The vessel was designed for 40 psig. It failed at 195 psig forming 12 fragments. The article lists the weight and distance thrown for each fragment. The failure initiated in an axial direction near a welded joint. The crack then branched in a circumferential direction forming fragments. Baker discovered that the predicted projectile distances were low and the predictions failed to show the splitting of one end cap into two pieces. Using the exact missile geometries from

the test the prediction gave results that were 2 to 4 times too great.

M.R. Baum of Berkeley Nuclear Laboratories has also contributed to the understanding of fragment hazards from exploding pressure vessels. He has conducted experiments and derived models for projectile hazard prediction for both PLG and pressurized gas vessels.

Baum (1984a) improved upon an old model to predict the velocity of fragments generated by the disintegration of a gas pressurized containers. Baum conducted experiments and researched old experimental work to validate his new model. He found that the old model over predicted the velocities of fragments by a factor of two for failure at design pressures, and it under predicted the velocities of fragments generated by failure from overpressures, while his new model gives much better results.

Baum (1984b) reviewed experimental work that is on going at Berkeley into the generation of large missiles and the modelling techniques available. He found that previous work showed that for a brittle failure resulting in typically many small fragments the fragments with the largest kinetic energy have a relatively small amount compared to ductile failures, which result in typically one or two fragments. Because of the difference in kinetic energies the large projectiles are more dangerous than the smaller ones. He concluded that existing models for predicting the hazards from large projectiles are inadequate. He found them to be unduly pessimistic. He states that this is due to fact that these models do not take into account any leakage of the propelling gas around the fragments as the container expands.

In a recent journal article (Baum, 1988) we find again an indication that there should be a differentiation between the

missiles generated by PLG vessel failure and the missiles generated by pressurized gas vessel failure. Baum has devised a classification scheme for missiles as outlined bellow:

Classification of Missile Geometries

From cylindrical vessels

1 End cap missile
2 Rocket missile
3 Whole vessel missile resulting from an axial split
4 Single large fragment ejected
5 Single small fragment ejected
6 Fragments generated from disintegration

From spherical vessels

7 Hemispheric fragment
8 Rocket missile
9 Single large fragment ejected
10 Single small fragment ejected
11 Fragments generated from disintegration

Classification of Vessel Contents:

1(a) An approximately perfect gas
1(b) A non ideal gas
2 Liquefied gas at a temperature and pressure such that rupture initiated flash evaporation
3 Gas plus a Liquid where rupture does not initiate flash evaporation
4 Gas plus loose particulate
5 Gas or flashing liquid with a large solid volume which is free to move

This classification scheme allows classification of fragments generated based upon the fragment geometry and the contents of the vessel at the time of failure. For instance if we have a rupture that resulted in a single large fragment ejected from a cylindrical vessel containing a PLG we would classify it as a type 4-2 missile.

Baum uses this classification scheme to identify the models he derives for the upper limit of fragment velocities. He derives an equation to give an upper limit to the fragment velocity for as many types of missiles as possible. These equations are based upon the experimental work of himself and others. Figure 9 shows for which missile types there is enough data to derive an upper limit equation. This report concerns the equations for vessel contents of type 2. Baum has provided upper limit equations for two missile geometries but there is very little acceptable data available. Note that Baum's note (b) indicates that this data is for vessels with a fill level of 100% and lower fill levels are expected to give different results (see figure 9).

Figure 10 shows the dimensionless equation for missiles of type 2-2 (rocket missile resulting from failure of a cylindrical vessel containing a PLG) compared with available experimental data. Since this equation is derived from limited data Baum considers it a provisional one. The experiments were carried out with water at $T_{sat} \approx 320$ °C for pressure ratios of $145 \leq P_o/P_e \leq 155$ and dimension ratios of $N/\ell = 1.0$ and $12 \leq \ell/R \leq 24$. Figure 11 shows the dimensionless equation for missiles of type 7-2 (hemispheric fragment released from a spherical vessel containing a PLG) compared with available experimental data. This equation is also derived from a limited amount of data. The experiments were carried out with water at $T_{sat} \approx 230$ °C and pressure ratios of $49.5 \leq P_o/P_e \leq 60.5$.

Figure 9: Available data non-dimensional analysis of fragment velocities and distance thrown (Baum, 1988)

		Missile geometry[a]										
		1	2	3	4	5	6	7	8	9	10	11
Fluid[a] contents	1(a)	78	21	28	2	14	16	X	X	X	X	39
	1(b)	X	X	X	X	X	X	X	X	X	X	X
	2	X	4[b]	X	X	X	X	3[b]	X	X	X	X
	3	X	X	X	X	X	X	X	X	X	X	X
	4	X[c]	X[c]	X	X	X	X	X	X	X	X	X
	5	X	X	X	X	X	X	X	X	X	X	X

[a] Classified using the previously defined numbering system.
[b] Data for full vessels; partially filled vessels are expected to give different results.
[c] Available BNL data (4 tests for each case) show no clear trend, and hence no recommendation is made.

Figure 10: Upper limit equation for missile 2-2 compared with experimental data (Baum, 1988)

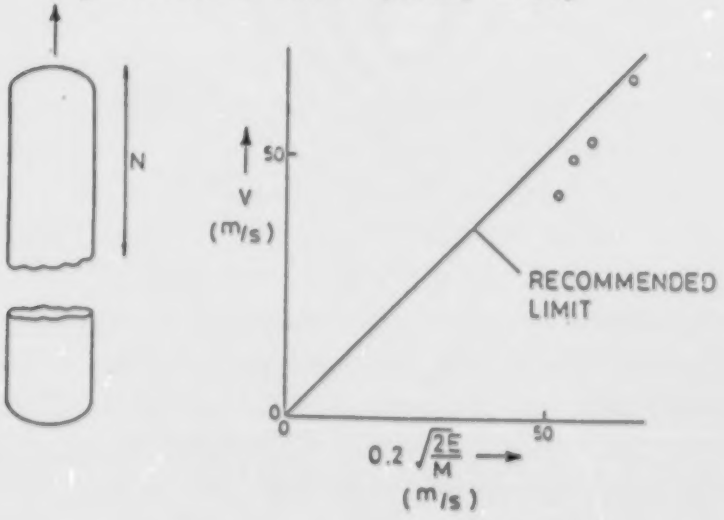
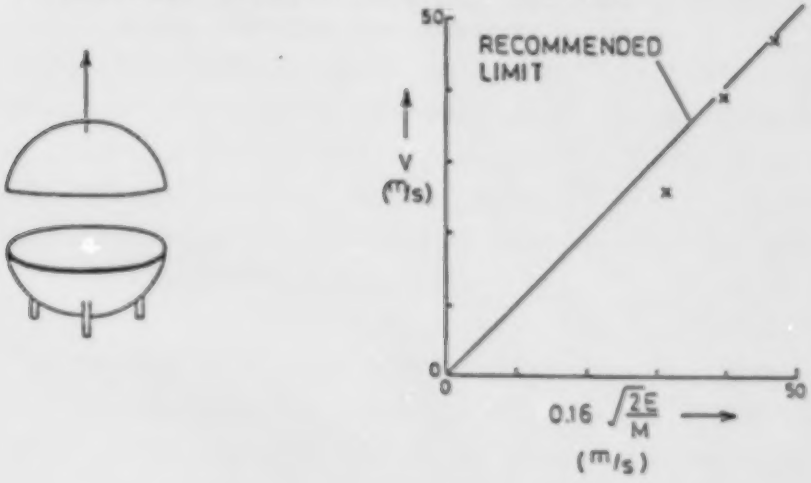
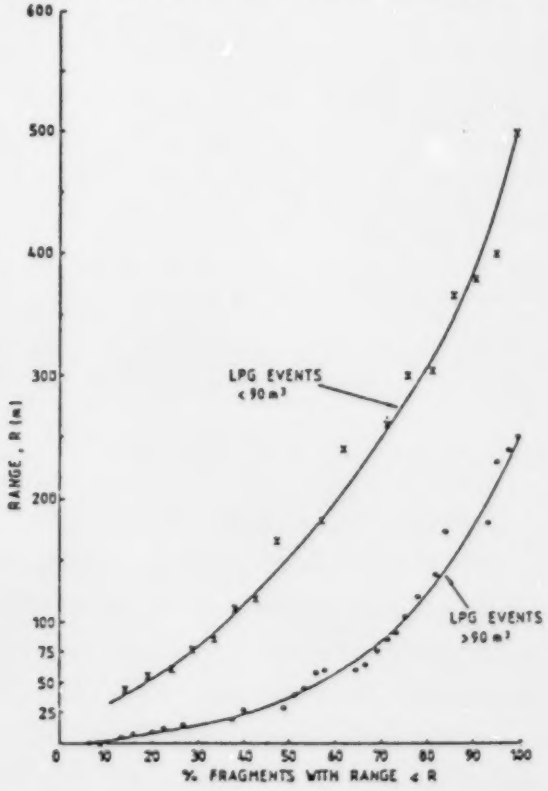


Figure 11: Upper limit equation for missile 7-2 compared with experimental data (Baum, 1988)



The UKAEA (Holden and Reeves, 1985) analyzed the data gathered in their accident survey. This analysis revealed a number of interesting facts. 80% of fire events that cause rupture result in missiles. BLEVE events usually produce four or less missiles and non fire events (explosions can occur from sudden depressurization of ladding caused by puncture) usually produce more than four. 80% of fragments from LPG accidents travel less than 200 m. Spheres produce more missiles than cylinders, spheres average 8.3 and cylinders average < 4. End tubs travel further than other types of fragments. Smaller vessels project fragments further than larger ones (see figure 12). Missiles tend to export fire with them.

Figure 12: Comparison of cumulative histograms of fragment ranges for LPG events where the vessels contained $> 90\ m^3$ and LPG events where the vessels contained $< 90\ m^3$ (Holden and Reeves, 1985)



O'Donoghue et al (1988) developed a model for numerically simulating the launch process for preformed fragments. This model does not predict the velocity or the distance fragments are thrown but it was included because it does offer some insight into the process of fragment formation. Their model is based upon a ratio called the expansion ratio which is defined as the ratio of the initial diameter of the container to the diameter at the time when gas begins to leak between the fragments (typically this ratio has been between 1.6 and 2.1). It is important since it gives an indication of how long the contents of a vessel can efficiently impart kinetic energy to fragments.

3-2-4 Blast and Missile Effects on Structures Modelling (see table 8)

The bulk of recent work on modelling the effects of explosions on structures has been done in the United Kingdom by the UKAEA, the HSE, the Explosion and Flame Laboratory and the Polytechnic of the South Bank. Also, the Southwest Research Institute in the United States has been involved in researching explosion effects.

A report of the Southwest Research Institute (Baker et al, 1978) reviewed research into the effects of blast loading on structures. This paper begins by discussing the differences between a blast wave generated by a TNT explosion and a blast wave generated from a pressurized container explosion. Baker et al (1978) then goes on to discuss several methods to estimate the potential damage from blasts.

The pressure-impulse (P-I) curve blast damage prediction method involves comparing blast loading and impulse on a structural element to graphs. These graphs indicate if a structural element will fail under the blast loading and impulse conditions (see page 47 for the derivation method). Another simple method for predicting blast damage is Briggs' method which relies on solving several differential equations. This method yields similar results to the P-I curve method. The other method Baker et al discuss is a more complex computer model which uses finite elements to predict the damage resulting from blasts. The least specific method is a table which lists the effects on various structures a variety of blast overpressures. As a final part to this paper Baker et al list five important points to keep in mind when designing a blast resistant structure.

Porter (1980) reviewed the effects of accidental explosions. He provides equations for the penetration of missiles into

metal (see equation 12) and concrete (see equation 13) as well as equations to predict the blast impulse and shock wave.

$$h_p^{3/2} = \frac{M_p V^2}{2g} \left(\frac{1}{17\ 400\ K^2\ d_p^{3/2}} \right) \qquad (12)$$

K is typically unity but has the dimensions of stress

Equation 13a is the modified Petry equation for the penetration (X) of a missile into infinitely thick concrete. Equation 13b is the relation between the penetration into infinitely thick concrete to the thickness (T) that is just penetrated by the same missile. Equation 13c is the equation to find the penetration (X_1) into a concrete wall of finite thickness.

$$X = 12\ K_p\ A_p\ \log_{10} \left(1 + \frac{V^2}{215\ 000} \right) \qquad (13a)$$

K_p is dependent on the crushing strength of the concrete
$K_p = 0.004\ 78$ for a crushing strength of 3200 psi
$K_p = 0.002\ 82$ for a crushing strength of 4700 psi

$$T = 2\ X \qquad (13b)$$

$$X_1 = \left(1 + e^{-4 \left(\frac{tW}{X} - 2 \right)} \right) X \qquad (13c)$$

Pritchard (1983) discusses work done by the Explosion and Flame Laboratory on the effects of blast waves on simple cantilever structures. Pritchard placed mild steel and aluminum rectangular cantilevers and mild steel tubular cantilevers in a 69 m long 1.2 m diameter tunnel closed at one end. He then detonated methane air mixtures at the closed end. The explosions generated peak overpressures and rise times that are typical of vapour cloud explosions. Pritchard

measured the blast overpressure and the deflection felt by the cantilevers. He also predicted the deflection felt by the cantilevers from elastic-plastic theory and compared them to the experimental results. This showed that the predictions and the experimental results were in agreement.

Brown and Nolan (1985) used the same explosion tunnel as Pritchard to test $1/40^{th}$ scale models of cylindrical pressurized storage vessels. The maximum blast speeds were found to be at $3/8^{ths}$ of the tunnel length from the closed end, the test section was located at $5/8^{ths}$ of tunnel length from the closed end because this is where the blast velocities most resembled typical values. Brown and Nolan carried out 260 explosions with a variety of cylinders some with stiffening rings, some with wind spoilers (common on some storage sites) and different length to diameter ratios (ℓ/d). They measured the blast overpressures and the damage to the cylinders. Damage to the cylinders was measured by the amount of plastic deformation each cylinder sustained. Brown and Nolan discovered that: the drag loading phase of the pressure wave caused the damage, cylinders with larger ℓ/d ratios sustained the most damage, the presence of stiffening rings increased the resistance to damage and the presence of wind spoilers decreased the resistance to damage. They also compared their experimental results with models to predict the deformation of their structures. They used "Robert's" approach and a modified node summation technique to predict the damage to the cylinders. Both models agree well with the experimental results.

Neilson (1985) conducted experiments to determine equations for the perforation of mild steel plates. These experiments consisted of projecting flat non-deforming cylinders at flat plates and measuring penetration. The experimental results were then analyzed non-dimensionally. He discovered that for long missiles (missiles with a ℓ_p/d_p ratios < 13) perforation

is not dependent on the ℓ_p/d_p ratio. Equation 14 is Neilson's equation to predict the perforation of long missiles. For short missiles (missiles with a ratios ℓ_p/d_p < 13) there was not enough data to derive an equation with any confidence.

$$\frac{E}{ud_p^3} = 1.4 \left(\frac{h_p}{d_p}\right)^{1.7} \left(\frac{w}{d_p}\right)^{0.6} \qquad (14)$$

Valid for:

$$4 \leq w/d_p \leq 22$$
$$\ell_p/d_p \geq 13,$$
$$0.14 \leq h_p/d_p \leq 0.64$$

Jowett (1986) reviewed the data and modelling work available from past experiments and used this data to derive equations to predict the perforation of mild steel plates. Equations are provided for short flat headed cylinders (see equation 15) (Jowett considers short missiles to be missiles with ℓ_p/d_p ratios of $\leq$ 10), long flat headed cylinders (Neilson's long flat headed cylinder missile equation 14) and pointed nosed missiles. He considers only hard missiles with a velocity of 25 to 300 ms^{-1}, target width to height ratios of > 2 and thickness to height ratios of > 10. Jowett concludes that both the pointed nosed missile equation and the short flat headed cylindrical missile equations agree with experimental results. He also states that non perforating impacts can be predicted analytically but perforating ones can not.

when $w/d_p > 2$:

$$\frac{E}{ud_p^3} = 1.32 \left(\frac{h_p}{d_p}\right)^{1.74} \left(\frac{w}{d_p}\right)^{0.61} \quad \text{for } 0.1 < \frac{h_p}{d_p} < 0.25 \qquad (15a)$$

$$\frac{E}{ud_p^3} = 0.38 \left(\frac{h_p}{d_p} \right)^{0.84} \left(\frac{w}{d_p} \right)^{0.61} \quad \text{for } 0.25 \leq \frac{h_p}{d_p} < 0.65 \qquad (15b)$$

when $2 < w/d_p < 12$:

$$\frac{E}{ud_p^3} = 6.0 \left(\frac{h_p}{d_p} \right)^{1.74} \quad \text{for } 0.1 < \frac{h_p}{d_p} < 0.25 \qquad (15c)$$

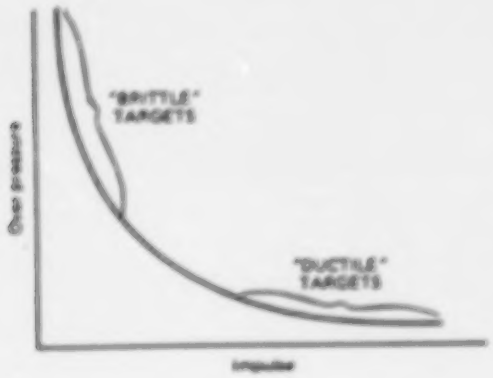
$$\frac{E}{ud_p^3} = 1.73 \left(\frac{h_p}{d_p} \right)^{0.84} \quad \text{for } 0.25 \leq \frac{h_p}{d_p} < 0.65 \qquad (15d)$$

Scilly and High (1986) review existing methods for predicting blast damage. They discuss the P-I, the stand off distance-explosive yield (R-W), the look up table and the impulse / critical methods for predicting blast damage to structures.

Scilly and High provide the equations to generate the P-I and the R-W graphs. Equation 16 will give the P-I curve of damage (also see figure 13). A draw back of the P-I method is the lack of data for structural elements; to use this method the minimum impulse to cause damage to a structural element must be known. Equation 17 is the R-W curve equation for any structure. The values of the coefficients A, B and C must be derived experimentally. They recommend that either the P-I or the R-W method be used to predict the damage from an explosion depending on what information is available and that the traditional look up table not be considered as accurate.

$$\frac{P}{P_i} - 1 = \frac{I}{I_i} - 1 \qquad (16)$$

Figure 13: General shape of a failure curve derived for a structural element from equation 16 (Scilly and High, 1986)



$$R_s = \frac{A\, W^{1/3}}{\left(1 + \frac{B^2}{W} + \frac{C^5}{W^2} \right)^{1/6}} \qquad (17)$$

Table 4: Fire Impingement Modeling

Title / Date	Author(s)	Sponsor	Focus	Findings	Recommended Further Work	Comments
Effects of Fire on LPG Tank Cars 1974	L. J. Hoxie	Association of American Railroads	- theoretical evaluation of the effects of fire on a tank car	- a tank car's survivability can be increased by raising the pressure relief valve setting - fill level should be as high as possible to decrease the time to liquid fill	- experiments should be conducted to determine the effects of temp and density stratification on pressure	- later work questioned conclusions - very brief but much data
Development of a computer Program for Modeling the Heat Effects on a Railroad Tank Car 1973	G. G. Greene	Federal Railroad Administration	- preliminary attempt to model the effect of fire engulfment	- no conclusions	- more accurate model for energy transfer to vapour space required - modification needed to account for non equilibrium of liquid - needs to include the ability to have a tank car on an angle	- provides a basis for future work - attempts to predict failure of a pressure vessel
Thermal Response Analysis of LPG Tanks Exposed to Fire 1988	M.U. Audemir U.E. Magapu A.C.M. Sousa J.C.S. Venart	University of New Brunswick Department of Mechanical Engineering	- development of a numerical model for LPG tanks engulfed in flames - experiments conducted to validate it	- model's pressure relief valve discharge times, internal pressure and temperature are in good agreement with the test results	- detailed analysis is required to determine the relation between discharge coefficient and void fraction overpressure	- uses two dimensional analysis - assumes plane of symmetry down center of tank

— for modelling work from 1975 to 1987 see Table 5 —

Experiments and Modeling: An Overview With Particular Reference to Fire Engulfment 1988	K. Maddie	Health and Safety Executive	- reviews models and experiments that exist to validate them	- for a given heat flux the smaller the tank and the lower the fill level the shorter the time to rupture - improvements in modeling of pressurized liquid have been made recently	- models need to be developed to model partial engulfment and jet fire impingement (this will probably require 3D modeling) - experiments of jet fires and partial engulfment need to be done	- lack data for non cylindrical vessels
Assessment of Mathematical Models For Fire and Explosion Hazards of Liquefied Petroleum Gases 1989	M.P. Crocker S.H. Napier	University of Toronto Department of Chemical Engineering and Applied Chemistry	- reviews mathematical models for fire engulfment	- one model for quiescent condition jet fires is seen as adequate to predict thermal hazard (Becker's) - for windy conditions the solid flame model using equivalent cylinder is the best - the BLEVE model gives theoretical maximum blast effects - BLEVE fire balls seem to behave differently from others so the stationary ground level model should be used since it gives the most pessimistic results	- rising fire ball models require further development - BLEVE blast model needs a more detailed aerodynamic model for explosive yield	- for jet fires in quiescent conditions there is a lack of agreement on view factors (one term of equation) - TNT was used to express yield equivalent (there is some uncertainty over what the equivalence should be)

Table 5: Programs for Fire Impingement Modelling from Moodie (1988) revised by the authors

Model Title	Date	Originating Body (Author)	Modes of fire attack modelled	Vessel Contents modelled	Vessel Type	Modes of Protection	Comments
-	1975	FRA (Graves)	Engulfing fire	Pressurised liquified gases	Horizontal Cylinder	Uninsulated	Basic code in public domain
THECAR	1983	Queen's (Birk)	Engulfing fire	Propane	Horizontal Cylinder	Uninsulated, insulated, radiation shielding. Explosafe fusible plugs	Finite difference heat conduction three node thermodynamic model
ENGULF I	1984	HSE/SRD (Ramskill)	Engulfing fire	Liquified gases multi-comp.	Any	Uninsulated, insulated, water spray	A cuboid based model with three nodal points in the shell.
-	1984	UMB (Vermart)	Engulfing fire	Pressurised liquified gases	Horizontal cylinders	Uninsulated, internal protection inc. Explosafe.	First version based on CALSPAN modified to include valve interaction with heat transfer modes.
THECAR	1985	TDC (Birk/Davis)	Engulfing fire & 2D torch fire	Propane n-butane n-pentane propylene	Horizontal cylinder various orientations	Uninsulated, insulated, radiation shielding. Explosafe fusible plugs	Computer code predicts wall and lading temperatures, internal pressure, liquid level and time to failure
SAFIRE	1986	DIDS	Engulfing fire	Pressurised liquified gases	Any	Uninsulated	Wide ranging computer code for relief vent sizing which also includes external heat source
ENGULF II	1987	HSE/SRD (Ramskill)	Partial and full Engulfing fire & Jet flares	Liquified gases multi-comp. gases	Horizontal cylinder vertical cylinder	Uninsulated, insulated	Later version of ENGULF I in cylindrical coords, enhanced fire modelling.
HEAT-UP	1987	SHELL RESEARCH (Dalyman)	Engulfing fire	Pressurised liquified gases	Horizontal cylinder	Uninsulated, insulated	2-D computer code for horizontal cylinderical propane tanks, pressure relief valve operation is modelled accurately
PLGS-1	1987	UMB (Sousa)	Engulfing fire	Pressurised liquified gases	Horizontal cylinders	Uninsulated	Current UMB Code

Table 6: Fire Ball and Blast Overpressure Modeling

Title / Date	Author(s)	Sponsor	Focus	Findings	Recommended Further Work	Comments
Modeling of Vapour Cloud Dispersion and Deflagration After Bursting of Tanks Filled With Liquefied Gas 1979	D. Maurer K. Hess H. Giesbrecht W. Leuckel	Ludwighafen/Rhein Federal Republic of Germany	- provides a model for the prediction of fire ball size, blast overpressure and vapour cloud mixing	- results can be scaled to reflect full scale vapour releases - the model agrees well with the experimental work	- no recommendations	- 6 tests using various sizes of cylindrical tanks filled with propylene were conducted - provides an equation for fire ball size and blast overpressure - provides a model for vapour cloud mixing
The Effect of Conditions Prior to Loss of containment on Fire Ball Behavior 1982	A.F. Roberts	Health and Safety Executive	- discusses the effects of initial expansion from flash evaporation and the initial state of the liquid on cloud and fire ball formation	- maximum diameter of fire ball is insensitive to fuel type - the vapour pressure at the time of failure will effect the portion of gas released into the fire ball, the rate of combustion, probability of a vapour cloud explosion occurring and the thermal radiation output	- on recommendations	- provides equations for fire ball radius from two models, maximum diameter, fire ball duration and heat flux at a specific range
Thermal Radiation Hazards From Large Pool Fires and Fire Balls - A Literature Review 1982	J. Moorhouse M.J. Pritchard	British Gas Corporation	- provides an overview of fire ball modeling	- no conclusions	- experiments need to be carried out to determine change in diameter with time, the vertical rise and the variation in emissive power during the life time of the fire ball	- provides an equation for maximum fire ball diameter, fire ball duration and estimation of hazard distance - estimates fire ball size increase
Thermal Radiation Hazard From Fire Balls 1982	D.A. Libby J.E. Hound	University of Aston Department of Chemical Engineering	- provides a model based on small scale experimental fire balls (100 - 900ml)	- fire ball surface temperatures are 1300K for butane and 1500K for methane - spherical diameter for fire balls increase at a constant rate through combustion	- large scale experiments are required to validate the effects of scale up for the model	- 2 series of tests - 1st series, balls of 1.5 to 4g of butane were ignited and fire ball size elevation and duration were measured - 2nd series, balls of .24 - 1.5g butane and .07 - .6g methane were, correlations were found for maximum elevation, spherical diameter and duration with mass - model provided to predict the hazards to people from BLEVE fire balls

LB
pm

Table 7: Modeling of Projectiles

Title / Date	Author(s)	Sponsor	Focus	Findings	Recommended Further Work	Comments
Velocities of Fragments From Bursting Gas Reservoirs 1971	D.E. Taylor C.F. Price	Lockheed Propulsion Company Redlands CA	- improves a model for bursting of a gas pressurized sphere in a vacuum	- old model had serious flaws - new one is much more accurate	- no recommendations	- only for a specific failure mode and conditions (ie a sphere that ruptures into two halves in a vacuum)
Analysis of Tank Car Tub Rocketing in Accidents 1972	D.H. Preuss J.W. Sullivan D.J. Eiber	Association of American Railroads	- preliminary model of tank car tub rocketing	- distance traveled by tub is a function of the temperature and pressure of the lading, the length of the tub, the launch angle and the outage of the tank at the time of rupture - tank diameter was not a factor - lading type was not a factor - the worst combinations of variables gave a distance traveled of 1220m to 3350m - outage has a significant effect: the range of rocketing decreased rapidly with the level of the lading in the tank - the ranges calculated are maximum upper bounds since the assumption was made that 100% of the available energy would go into rocketing	- no recommendations	- tub rocketing model was developed based on isentropic expansion of the lading - calculations assumed that 100% of the energy released goes into rocketing - report speculates that short tubs will be less likely to travel a straight line - model validation is difficult since accurate data is hard to come by in accident reports
Initial Velocities Attained By Plant Generated Missiles 1980	G. Munday	Insurance Technical Bureau	- provides a model for projectile hazards	- following this model an initial acceleration should be supplied for fragments projected by fluid jets and no initial acceleration should be provide for other fragments - stored energy methods are not a good model to use unless an upper limit is desired	- experiments are needed to provide data to validate this model - computer programs need to be written to handle this modeling approach	-no attempt should be made to present results from this model - each rupture case of interest should be considered seperately
Assessment of Missiles Generated by Pressure Component Failure and its Application to Recent Gas Cooled Nuclear Plant Design 1980	J. Tulacz D.E. Smith	Central Electric	- derives several models to predict the distance fragments are hurled and the penetration damage they cause	- to evaluate the protection given by a barrier from the failure of a pressure vessel the penetration models should be used with a mode of failure with one missile occurring - recommends that their model be used to give an upper bound to the distance a missile will be projected for missiles of types (a) & (b) (type (a) is a flat round section of the vessel, type (b) is a valve from the vessel and type (c) is a rocket missile)	- experiments are needed to validate an acceptable velocity model for type (a) missiles -work is needed to see how the penetration models relate to the case of irregularly shaped (ie natural) missiles - work is also needed in the area of penetration of mild steels	- report identifies three different types of missiles to analyze - provides an equation for the velocity of a missile of types (a) & (b) - offers two unvalidated methods to estimate the velocity of a missile of type (c) - provides equations to predict missile penetration and scabbing thickness on a reinforced concrete wall with cylindrical missiles - provides a way of relating natural missiles to cylindrical missiles

Table 7: continued

Title / Date	Author(s)	Sponsor	Focus	Findings	Recommended Further Work	Comments
The Velocity of Missiles Generated By The Disintegration of Gas Pressurized Vessels and Pipes 1984	M.R. Baum	Berkeley Nuclear Laboratories	- provides a model for the velocity of fragments generated by the disintegration of a gas pressurized container and validates it	- old model over predicts velocities by a factor of 2 for failure at design pressures - old model under predicts velocities for failure by overpressure	- no recommendations	- uses experimental work (new and old) to validate the new model and refute the old - model is also found to be a good one for the failure of pressure pipes as well
Large Missiles Generated by the Rupture of Gas Pressurized Vessels: A Summary of Current Data From Experiments at CEGB, Berkeley Nuclear Laboratories 1984	M.R. Baum	Berkeley Nuclear Laboratories	- discusses experimental work and preliminary models of three types of missiles	- experimental data already gathered suggest that the existing models are inadequate (ie to conservative) for large missiles - brittle failures result in many small fragments here none have a large kinetic energy - ductile failures result in few large (1 or 2) fragments which have a large kinetic energy	- model development is necessary to help predict the results of catastrophic failure of pressure vessels - energy is lost to leakage around fragments and models need to take this into account account	- no comments
Blast and Fragments From Bursting Pressure Vessels 1984	W.E. Baker	Southwest Research Institute, San Antonio Texas	- is a survey of prediction methods for blast and fragment characteristics of bursting pressure vessels	- describes the state of the art for predicting the blast and fragment characteristics for explosions involving flash evapourating liquids as poor to fair - describes the state of the art for predicting the blast and fragment characteristics for explosions involving compressed liquids as zero to poor	- experimental work is needed towards understanding blast and fragment characteristics for both flash evaporating and compressed liquids	- provides has a graph to predict maximum fragment range for gas pressurized vessel rupture - provides a graph to predict blast from gas pressurized vessel rupture
Post Test Assessment of Blast and Fragment Effects of Explosive Failure of a Large Steel Containment Shell Model During Pneumatic Testing 1984	W.E. Baker	Southwest Research Institute, San Antonio Texas	- describes the test results of a steel containment vessel that was ruptured explosively and compares it to the predictions made based on a model	- failure initiated axially near a welded join with a stiffener then branching circumferentially - predicted projectile distances hurled were to low - revised calculations (using the same model with actual fragment geometry) were 2 to 4 times to great	- work is needed on modeling of projectile distance hurled to make better predictions	- pressurized a vertical cylinder to 195psig that was designed for 40psig - produced 12 fragments - head separated into 2 pieces which was not predicted - gives a table of mass and distance hurled for fragments

Table 7: continued

Title / Date	Author(s)	Sponsor	Focus	Findings	Recommended Further Work	Comments
Fragment Hazards From Failures of Pressurized Liquefied Gas Vessels 1985	P.L. Holden A.B. Reeves	United Kingdom Atomic Energy Authority Safety & Reliability Executive	- analyses fragment range frequency for historical accidents involving pressurized liquefied gases	- models for pressurized liquefied gases are not developed enough - 80% of fire events that rupture result in missiles - BLEVE events project 4 or less missiles - non fire events project more than 4 - 80% of fragments from LPG accidents travel less than 200m - spheres produce more missiles than cylinders (average 8.3 vs ave < 4) - end tubs travel further than other fragments - smaller vessels project missiles further - missiles tend to export fire with them	- experiments are needed to investigate the effect of vessel size on missile range - work to develop a model specifically for fragments from pressurized liquid vessel failure is needed	- some confusion over use of the term BLEVE - evacuation ranges are based on missile distances recommended in a 1972 report since 1972 people and fire fighters have been killed by missiles
Disruptive Failure of Pressure Vessels: Preliminary Design Guidelines for Fragment Velocity and Extent of the Hazard Zone 1988	H.R. Baum	Berkeley Nuclear Laboratories	- gives upper limits for projectile hazards	- model is valid - can be used to indicate an upper limit of the ranges and velocities of projectiles from those modes of failure considered	- no recommendations	- no comments
Dynamic Launch Process of Preformed Fragments 1988	D.E. O'Donoghue W.W. Predebon C.E. Anderson	Michigan Technological University and Southwest Research San Antonio Texas	- provides a model for determining the stresses in cylinders under explosive forces	- shock in circumferential direction causes expansion of vessel - larger expansion ratios mean larger forces since gasses are contained longer	- no recommendations	- requires independent measurement of expansion ratio - expansion ratio is the ratio of initial DIA to the DIA at the time when gas begins to leak between the fragments (between 1.6 - 2.1) - equired a value for expansion ratio from other experiments and their own - model is validated with experiments

Table 8: Blast and Missile Effects on Structure Modeling

Title / Date	Author(s)	Sponsor	Focus	Findings	Recommended Further Work	Comments
Methods For Prediction of Damage to Structures From Accidental Explosions 1978	W.E. Baker P.S. Westine P.A. Cox	Southwest Research Institute	- discusses blast effects on structures - discusses differences in pressure waves between TNT and other types of explosions	- outlines the design criteria (qualitatively) for buildings suited to withstand accidental explosions based on the models introduced	- no recommendations	- once the blast loads are known damage can be quickly calculated by simple models or more exactly from complex computer models - P-I curve is one simple model discussed - Briggs' method relies on solving a differential equation (results are quite similar) - computer models rely on node shape and finite element methods
Generation of Missiles and Destructive Shock Fronts and Their Consequences 1980	W.H.L. Porter	United Kingdom Atomic Energy Authority	- general review of the effects of accidental explosions	- no conclusions	- no recommendations	- provides equations for the penetration of missiles into metal and concrete and for the determination of blast impulse and shock wave
An Experimental and Theoretical Study of Blast Effects on Simple Structures (Cantilevers) 1983	D.K. Pritchard	Explosion and Flame Laboratory	- outline the results from experiments involving cantilevers in vapour cloud explosions	- the preliminary comparisons for elastic deformation showed the experimental procedure works - fair agreement between test results and elastic plastic theory were obtained	- information needed on the dynamic material properties of metals - information needed on the aerodynamic characteristics of structures as they deform - further experiments should be carried out to provide more data on a wider variety of loadings and dimensions	- used a 69m long by 1.2m diameter cylinder closed at one end as a test tunnel - methane air mixtures were detonated at the closed end generating peak overpressures and rise times which were representative of vapour cloud explosions - aluminum and mild steel rectangular, mild steel tubular cantilevers were tested - equations of deformations were then developed based on the results and elastic - plastic theory

Table 8: continued

Title / Date	Author(s)	Sponsor	Focus	Findings	Recommended Further Work	Comments
The Effect of External Blast on Cylindrical Structures 1985	D.M. Brown P.F. Nolan	Polytechnic of the South Bank Department of Chemical Engineering	- scale cylindrical storage vessels where subjected to simulated vapour explosions and the deformation effects where measured	- the drag loading phase of the pressure wave caused the damage - the model developed showed good agreement with the experiments and an actual accident - increased L/D ratios meant greater damage - stiffening rings increased resistance to damage - wind spoilers decreased resistance to damage	- no recommendations	- models 1/40 of scale - tests carried out in the same test tunnel as above - maximum velocities occurred 3/8 of the way down the length and the models where placed 5/8 of the distance - 260 explosions where carried out
Empirical equations For The Perforation of Mild Steel Plates 1985	A.J. Neilson	United Kingdom Atomic Energy Authority	- experiments were conducted on penetration of mild steel plates by flat end cylinders and the results analyzed dimension-lessly to derive representative equations	- equations derived from experiments for missiles with L/D ratios of > 13 give a good correlation to the tests - for short missiles L/D ratios < 13 not enough data exists for confidence in the derived equation - missiles with L/D ratios > 13 showed no dependence on length	- additional data for short missiles is required to improve the equation for short missiles	- non deforming cylinders were projected at plates to find the maximum energy not giving perforation and the minimum energy giving perforation - results from other experimental studies are discussed
The Effects of Missile Impact on Thin Metal Structures 1986	J. Jowett	United Kingdom Atomic Energy Authority	- review of previous work on projectile penetration is used to develop a model for prediction of penetration of mild steel plates by flat ended cylinders and pointed nosed missiles	- pointed missile model agrees well with published data - short missile model agrees well with published data - non perforating impacts can be predicted analytically but perforating impacts can not	- work is needed to determine the influence of target welds, the effect of non normal impacts and the behavior of thin curved shell targets	- hard missiles are considered with speeds of 25 to 300m/s and targets with width / D > 2 and thickness / D > 10 - provides equations of penetration for flat head missiles both short and long (long is L/D ratios of > 10) - no perforation models exist for round nosed missiles - provides an equations for pointed nosed missile penetration

Table 8: continued

Title / Date	Author(s)	Sponsor	Focus	Findings	Recommended Further Work	Comments
The Blast Effects of Explosions 1986	N.F. Scilly W.G. High	Health and Safety Executive	- discusses several methods of calculating blast damage and their draw backs	- to predict the effects of explosions on structures either P-I, R-W curves or the impulse / critical method should be used - the table method should only be used as a last resort when data is not available	- no recommendations	- smaller explosions need larger overpressures to do the same amount of damage as larger explosions because of the duration of the blast wave - outlines several methods of determining the blast effects on structures, tables relating overpressure to damage, P-I (pressure impulse), R-W (stand off distance explosive yield) curves plus an alternative method based observations of explosions

3-3 Case Studies (see table 9)

A variety of case studies have been compiled into table 9. The Railroad Tank Car Safety Research and Test Project of the AAR and the FRA compiled a report containing tank car accidents from 1958 to 1971 (Westin, 1971). They also conducted individual investigations, which contain more detail, of major accidents that occurred during the programs existence (Reedy, 1970 and Reedy, 1971). The table also includes the reports of two special commissions of inquiry into accidents in Canada (Grange, 1980 and Magee, 1985) as well as an internal study of a PLG truck accident at Salmon Arm commissioned by Transport Canada Transport Dangerous Goods Directorate. The UKAEA also compiled a list of accidents involving pressurized liquefied gases from 1958 to 1986. This compilation contained some basic analysis which was taken from a report by Holden and Reeves (1985) (see section 3-2-3, figure 12). The table also contains journal articles and reports that report on non rail accidents; a pneumatic burst (Christ, 1979), storage sites (Van der Schaaf and Steunenberg, 1983 and Pietersen, 1988) and a process cylinder (McHenry et al, 1987)

3-3-1 Fill Conditions

With the exception of the following two case studies, few accident studies have enough information to establish fill conditions at the time of rupture.

Fill level was calculated in one detailed study of a rail tank car accident that was conducted by the Railroad Tank Car Safety Research and Test Project (Reedy, 1971). The accident occurred outside Houston Texas. Sixteen cars were derailed and two cars of vinyl chloride were punctured and started to burn. After 45 minutes the first car exploded followed almost immediately by the second. The remains of the first car, ESMX 4804, showed the impact puncture hole to be 3 1/2 by 5/16 inches. Since the orientation of the tank was known

from photographs calculations were done to estimate the amount of vinyl chloride that could escape in 45 minutes. The calculations showed that the tank had a fill level of 70% when it ruptured and that the temperature of the lading was under 60 °F. At rupture the tank formed two rocket tubs; one making up the majority of the car (over 3/4) was thrown 100m. The smaller tub was thrown 68 m.

Another case study that refers to fill level is the Magee inquiry (1985). In this case rupture was induced by impact at a switching yard. The ruptured tank blew its head off even though it was listed as "empty, last containing butane". The rail tank car had 55 to 70 psi of butane and natural gas inside it (ie 800 to 1200 lb). Upon impact from another car, in the coarse of switching, the first car exploded and the head was blown 38 m.

3-3-2 Projectiles

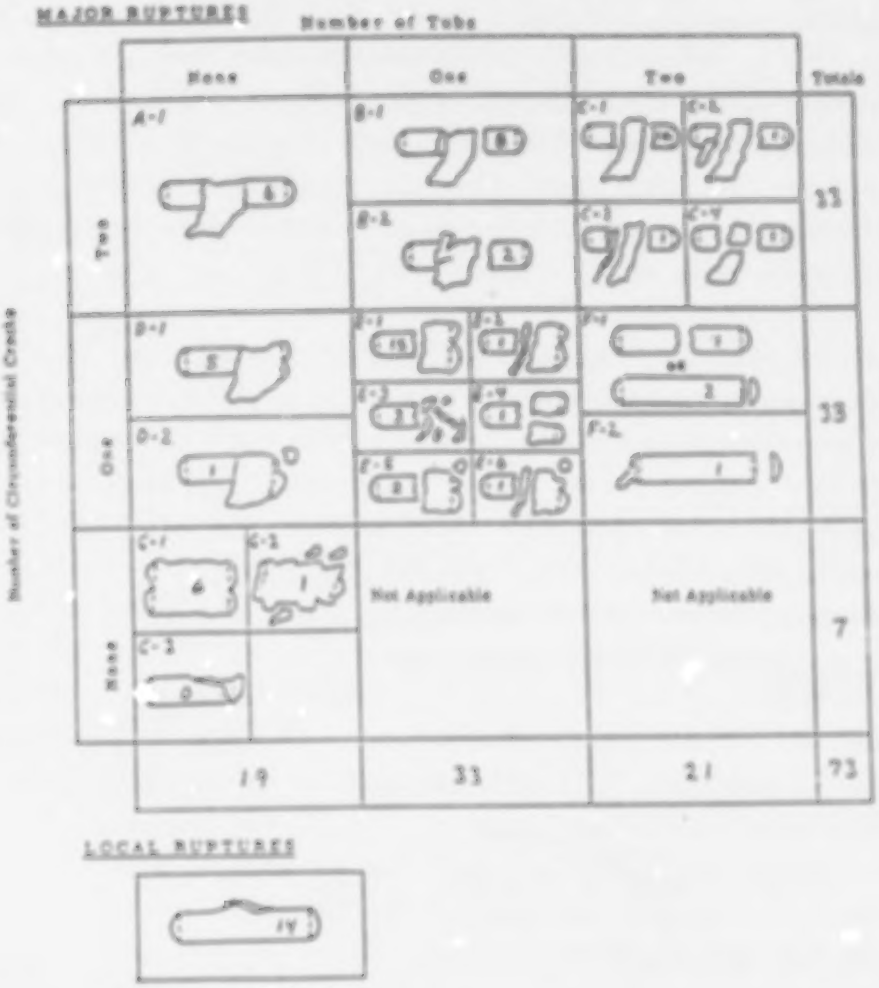
All the case studies referenced contain information about the distances that generated fragments are thrown. Most case studies do not come from a detailed investigation of an accident scene where all the fragments are recovered and measurements taken of the fragment mass and distance thrown. Generally they are put together from eyewitness accounts and photographs; so the information on fragments omits any mention of mass and probably only accounts for the largest pieces. However there are a few case studies that do go into detail about all the fragments and even where the rupture originated on the tank, such as: the report on the Salmon Arm by Charlton and Heslop (1984), the report on a truck accident in Nijmegen by Van der Schaaf and Steunenberg (1983) and the analysis of the Mexico City disaster (Pietersen, 1988) both written for the TNO. Note the Grange commission and the Magee commission were commissioned to asses the operational

lapses, mechanical failures or human error that caused these accidents and how to prevent similar accidents in the future not the specific physical details of each missile generated..

It would be interesting to see what similarities exist between the distance fragments are hurled during experiments where rupture occurred and the distance fragments are hurled from accidents (see section 3-3-3, figure 15). We see from figure 15 that the distance fragments are hurled from accidents is slightly longer than the distance fragments are hurled from experiments. This may be because accident reports do not tend to be as detailed as experiments and some smaller fragments may not have been found or documented in these reports.

The accident compilation report of Westin (1971) contains a figure (see figure 14) that shows the rupture configuration (failure modes) of the accidents listed. The type of failure configuration of each accident was grouped by similar patterns. Many of these patterns (A, B, C, D and E) result from the most common failure mode. A crack originated along the tank axis at the top and then as it propagates it branches in a circumferential direction one or many times to form fragments. Other patterns (G and F) do not result from this sequence of events. In type G ruptures the crack propagates only in the axial direction often splitting the tank open without forming any fragments. The type F rupture patterns result from a crack that originates in a circumferential direction and circumvents the tank forming a tub.

Figure 14: Summary of rupture configuration (Westin, 1971)



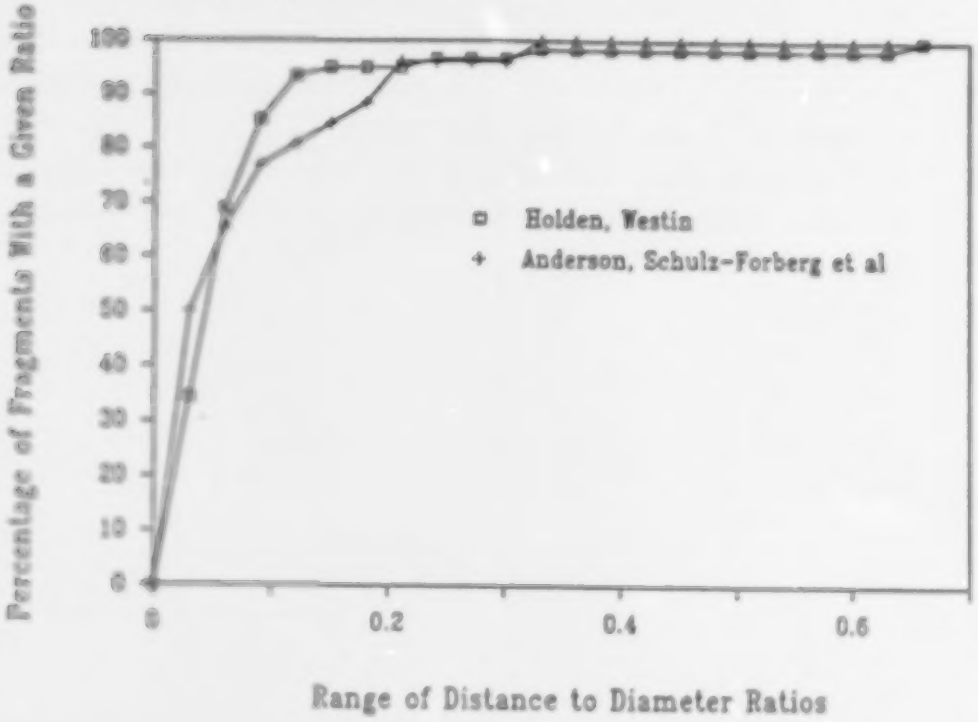
3-3-3 Case Studies Compared to Experimental Studies

The compiled accident summaries of Holden (1986) and Westin (1971) give enough information to plot a histogram of the dimensionless ratio of tank diameter divided by fragment distance hurled. Some articles about fire engulfment tests where catastrophic ruptures occurred also contain enough information to plot similar histograms. The full scale rail tank car fire engulfment test of the AAR and the FRA

(Anderson and Norris, 1974) and the three small stationary storage vessel engulfment tests done by Schulz-Forberg et al (1984) all contain the necessary information. Figure 15 is a comparison of the cumulative histograms for the 61 fragments recorded in Holden's (1986) and Westin's (1971) compiled accident reports and the 21 fragments from the fire engulfment tests of Anderson and Norris (1974) and Schulz-Forberg et al (1984).

The curves of these cumulative histograms are slightly different. The curve from the fire engulfment test data is not as smooth and rises less sharply that the curve from the accident report data. This difference may be caused by the sample sizes for the two histograms (61 for the accident reports and 27 for the experiments). Another difference that should be noted is the number of fragments from each rupture. The accident report data recorded 61 fragments from 60 ruptures. and the experimental data recorded 27 fragments from 4 catastrophic failures. Reports on experimental studies record all vessel fragments including the smaller ones while accident reports tend to neglect these less noticeable projectiles. Because of this accident reports may give a misleading representation of the projectile hazards from PLG container explosions.

Figure 19: Comparison of data, from case studies and experimental studies, showing the distance fragments are hurled after catastrophic failure. Case studies compiled by Holden (1986) and by Westin (1971) (total of 61 samples) is compared with experimental work done by Anderson and Norris (1974) and Shulz-Forberg et al (1984) (total of 27 samples)



3-3-4 Blast Overpressure

It is rare for accident reports to refer to the blast overpressure, since it is something that eye witnesses are not equipped to measure. Only Pietersen (1988) makes any reference. This be infers from the high degree of blast damage around the site of the Mexico city disaster amongst private homes. It is clear that accident reports are not valuable for estimating the blast overpressures generated from PLG vessel explosions and experiments are probably the only reliable method of obtaining this information.

3-3-5 Fire Ball

Several reports refer to fire balls that lasted for y seconds and rising to a height of x meters. These values come from eyewitness accounts and are not accurate enough to be of much use. Reedy (1971) makes reference to an area that was "blackened" by fire but he does not state if this was due to a fire ball or just the spilled fuel burning and being spread by the explosions. We see that accident reports are of little value for estimating the size and duration of fire balls. Again experiments are the best providers of this information.

Table 9: Case Studies

Title / Date	Author(s)	Sponsor	Focus	Findings	Recommended Further Work	Comments
Sequence of Events Following Crescent City Derailment 1970	C.E. Reedy	Association of American Railroads	- report on events surrounding the accident at Crescent City	- no conclusions	- no recommendations	- 16 cars derailed of which 10 had PLG as lading - 4 explosions occurred over a 55 hour period - report gives fragment distances buried
Summary of Ruptured Tank Cars Involved in Past Accidents 1971	W.E. Westin	Association of American Railroads	- a listing of data from accidents involving explosions	- no conclusions	- no recommendations	- no reference made to fill level at time of accident - covers the period from 1958-1971 - gives distances missiles thrown
Sequence of Events Following Houston Texas Derailment 1971	C.E. Reedy	Association of American Railroads	- report on events surrounding the accident at Houston Texas	- no conclusions	- no recommendations	- 16 cars derailed - 2 explosions occurred over a short period of time - report gives fragment distances buried
Analysis of the Pneumatic Burst of a Large Seamless Steel Pressure Vessel in Natural Gas Service 1979	D.W. Christ	U.S. Department of Transport	- report on the metallurgical analysis of the pressure vessel that failed in an accident near Litchfield	- the cylinder ruptured due to environmentally assisted cracking due to the presence of hydrogen sulfide in the natural gas	- no recommendations	- one of 12 new pressurized gas cylinders ruptured on the back of a tube trailer - rupture was at 2200-2500psi during filling - 11 fragments were formed and they were thrown between 200 and 2000 ft - report gives distance each fragment was thrown
Report of the Mississauga Railway Accident Inquiry 1980	G.M. Grange	Canadian Transport Commission	- report on the events surrounding the accident at Mississauga	- accident caused by overheated bearing	- research should be conducted into the adequacy of safety devices presently in tank cars - also a number of operating procedure changes are recommended	- 23 cars derailed of which 3 contained propane - 3 explosions occurred with in 1/2 an hour of the accident - contains the distances fragments buried

Table 9: continued

Title / Date	Author(s)	Sponsor	Focus	Findings	Recommended Further Work	Comments
Summary Report on Propane Bulk Truck Rupture Near Salmon Arm, BC June 13, 1984 1984	B.S. Charlton J.M. Heslop	Transport Canada, Transport Dangerous Goods Directorate	- report on the events surrounding the accident near Salmon Arm	- rupture was due to the reduction of the steel strength resulting from over heating from a fire - the propane flow rate to sustain the fire was far less than that required to activate the excess flow valve - the leak was caused by the shearing off of an external pump's hose attachment	- various improvements on design and operating procedures were recommended to improve safety	- 3000gal tank truck exploded - tank fixtures where damaged in accident which caused leakage - tank was situated on a hill over a train track and when the tank BLEVed the tank rocketed into a passing train derailing freight cars.
Report of the Inquiry into the Failure of UTLX 19855 on Feb 20 1984 to the CN Company's MacMillan Yard in the Township of Vaughan Ontario 1985	J. Hagee	Canadian Transport Commission	- report on events surrounding the accident at Vaughan Ontario	- failure caused by impact	- no recommendations	- an empty tank car ruptured in a switching yard - report is concerned with who was responsible - it does give the distance the head was buried
Assessment of Missile Hazards: Relevant to Major Hazardfiles 1988	P.L. Holden	United Kingdom Atomic Energy Authority	- a listing of data from accidents involving explosions of tank cars, road tankers and storage vessels	- BLEVE events seldom create more that 6 fragments - non fire events project more fragments (average 3.08) compared to fire events (average 2.67) - end tabs are 3 times as likely to be projected axially than other directions - end tabs travel further than other missiles - if fire is the cause of catastrophic failure to a cylindrical vessel then there is an 80% chance of missiles being formed when the vessel explodes - mode of failure does not influence range - spherical vessels fail to more fragments than cylindrical vessels	- the following things need more measurements to yield conclusions - angle of launch from horizontal - distance projected (bouncing, deflection) - following needs more measurement - the difference in the number of fragments between fire and non-fire events - the direction of launch relative to the axis of the tank car	- suggests that for spheres the size influences distance and number of fragments (the larger the vessel the more and longer the fragments are thrown)
Investigation into the Circumstances Surrounding an Accident in Bergen Involving a Tanker 1983	J.G.S. Van der Schaaf C.V. Steenenberg	TNO	- outlines the events of a fire at a fuel station receiving a delivery of LPG from a road tanker	- tank ruptured in the vapour space at a place impinged by flame after thinning occurred - tank was subjected to temperatures of about 600+C at rupture site and pressure of between 1600 and 2100kPa - fire ball was 60m diameter and on top of a column 25m diameter and 25m high (or 10s)	- no recommendations	- road tanker had no safety valve but the storage tank did - tanker exploded after 25min of exposure to flame - tanker moved 6m, side of tanker buried 50m and parts buried as far as 125m - fill about 85% (400kPa) at time of rupture

Table 9: continued

Title / Date	Author(s)	Sponsor	Focus	Findings	Recommended Further Work	Comments
BLEVE in an LPG Storage Yard 1986	G.R. Collins	Stockton Fire Department, CA	- outlines the events at a LPG storage yard in california	- explosion caused by fire resulting from PRV malfunction and solar radiation - a PRV on a 10 or 25gal cylinder vented to release pressure (from solar exposure) and fragmented causing total loss and ignition	- no recommendations	- 5min after first other 10 and 25 gal cylinders were exploding causing flames to impinge on a 500gal tank - PRV of the 500gal cylinder began to vent after 8min and exploded causing a 90m high and 45m wide fire ball
Failure Analysis of an Amine - Absorber Pressure Vessel 1987	H.I. McHenry D.T. Read T.R. Shives	National Bureau of Standards	- report on the explosive failure of a amine - absorber pressure vessel	- failure occurred circumferentially adjacent to a repair weld near the base of the vertical cylinder - failure was caused by hydrogen stress cracking (800mm long and 90% deep crack)	- no recommendations	- the vessel came apart circumferentially near the base and the released propane exploded - the top 14m of the 18.8m tall cylinder rocketed 1000m
Analysis of the LPG Disaster in Mexico City 1988	C.M. Pietersen	TNO	- analyses the disaster in Mexico City by comparing it to existing disaster models	- models of vapour cloud dispersion are not adequate to predict clouds of this scale - models of fire ball size under predict the size seen here - the confined space of the storage facility helped the creation of overpressures	- models to predict the effects of overpressures need to be developed - models of the fire ball dimensions from BLEVE's are also inadequate and need work	- at Mexico City 9 major explosions occurred - the 2nd and 7th were the largest (0.5 on the Richter scale) - vapour cloud developed from pipe or cylinder leak and rose to 2m before it ignited causing an unconfined vapour explosion and damage to buildings and storage vessels, 1min later a BLEVE occurred which initiated other explosions - 44 of 48 cylinders that exploded had fragments that could be found and were thrown between 100 and 1200m - the other 4 cylinders fragmented into very small pieces

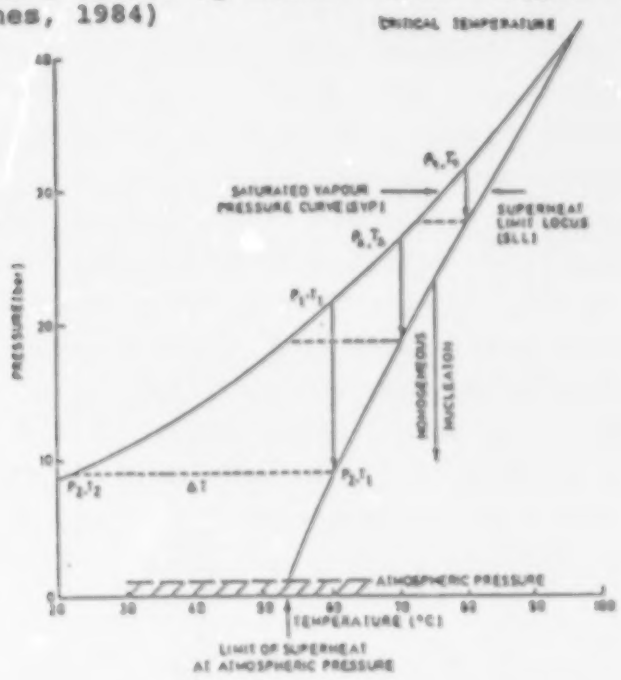
3-4 BLEVE Theory (see table 10)

Various people have tried to explain how BLEVE's occur. Table 10 outlines these attempts. There is one theory that is repeated in all attempts to explain BLEVE's, the superheat limit theory. Two other theories are discussed by McDevitt et al (1987). These other theories maintain that homogeneous boiling takes place only at the boundary between the escaping liquid droplets and the heated atmosphere. It should be noted that there is no conclusive evidence to support any theory.

The superheat limit theory as stated by Reid (1979), Jones (1986), Martinsen et al (1986), McDevitt et al (1987), Davenport (1988) and Dunn (1988) explains the mechanism of BLEVE's as follows. All PLG's have what is called a superheat limit. This limit is the maximum amount that the liquid can be superheated (see Figure 18) before it will homogeneously boil (ie spontaneously boil at once with out the need for nucleation sites).

When the temperature of a saturated liquid is increased normally it will begin to boil but this can only occur if there are nucleation sites. Nucleation sites are small nicks or rough surfaces that allow bubbles to form. If there are no nucleation sites then the liquid will become superheated. In the case of a BLEVE when the container looses its ability to contain the liquid (rupture) at the elevated pressure (where the boiling point is higher) the liquid in the container becomes instantly superheated. If the saturation temperature before the loss of containment is sufficiently higher than the atmospheric temperature then the liquid will reach its superheat limit and spontaneous homogeneous boiling will occur. This homogeneous boiling is the BLEVE explosion. The severity of this explosion can be determined from the ΔT between the saturated vapour pressure curve and the superheat limit locus (see Figure 16). Thus if a vessel lost its containment at P_1, T_1 then the explosion will be more severe than if the vessel lost containment at P_3, T_3 or P_4, T_4.

Figure 16: Graph of the saturated vapour pressure curve and the superheat limit locus for propane with the "paths" of BLEVE's marked by solid lines tipped with an arrow (Jones, 1984)



McDevitt et al (1987) advance another theory to explain BLEVE's (originally from Board and et al (1975)). The theory speculates that "as the vapour which is formed at the hot-cold interface collapses it causes a shock wave which in turn causes fine mixtures of the two fluids". For a BLEVE this means that as the liquid droplet is drawn out into the hot vapour or hot atmospheric air (heated by the fire) a vapour barrier is formed at the interface. This vapour barrier, which acts like an insulating blanket, is stripped off as the droplets pass through it. With this insulating barrier stripped off rapid evaporation can occur and it is this rapid evaporation acting on many droplets that is the BLEVE.

The other possible explanation given by McDevitt et al (1987) is a combination of the above two theories. When the vessel ruptures the liquid is sucked out of the rupture as droplets. With the rapid heat transfer from the vapour to the droplets these droplets

might exceed the superheat limit and each droplet would then homogeneously boil causing a BLEVE explosion.

Other papers also discuss the causes of BLEVE's and other observations that can be made about them. Walls (1979) states that not all of the liquid portion of a container will flash to a vapour in a BLEVE. This is consistent with the flashing liquid experiments discussed in section 3-1-2. Jones (1984) states that both homogeneous and heterogeneous boiling can lead to an explosion but explosions caused by heterogeneous boiling are less severe. Davenport (1988) says that BLEVE's occur more frequently and faster when fire impinges on the vapour space than when fire impinges on the liquid space. Dunn (1988) states that a common cause of vessel failure is due to weakening of the vessel shell from the sustained high temperatures of fire, which lowers the strength of the steel to a point such that rupture can occur below the PRV setting.

Table 10: Theory

Title / Date	Author(s)	Sponsor	Focus	Findings	Recommended Further Work	Comments
Possible Mechanism for Pressurized Liquid Tank Explosions or BLEVE's 1979	R.C. Reid	- Department of Chemical Engineering Massachusetts Institute of Technology	- provides a theory into the mechanism of BLEVE's	- no conclusions	- well conceived experiments are needed to prove or disprove this theory	- states that there is a limit to the degree of superheat that is attainable in a liquid - if a liquid that is superheated is depressurized and this limit is reached than sudden homogeneous boiling will occur
The BLEVE Part I & II 1979	W.L. Walls	National Fire Protection Association	- offers expanation of BLEVE's	- not all of the liquid portion of a container will flash to a vapour in a BLEVE	- need more projectile data	- no comments
Vapour Explosions Resulting From Rapid Depressurization Liquids - The Importance of Initial Temperature 1984	H.R.O. Jones	BP Research Center	- presents a theoretical explanation of the effect of rapid depressuriza-tion of a liquid stored at its vapour pressure	- homogeneous boiling leads to a more explosive event than heterogeneous, although explosive boiling can occur heterogeneously	- no recommendations	- states that there is a limit to the degree of superheat that is attainable in a liquid - if a liquid that is superheated is depressurized and this limit is reached than sudden homogeneous boiling will occur - has some backing of lab experiments
BLEVE's Their Cruses Effects and Prevention 1986	W.E. Martinsen D.W. Johnson W.F. Terrel	Energy Analysis Inc.	- offers explanation of BLEVE's	- no conclusions	- no recommendations	- uncertainties suround fire ball size
What Is a BLEVE? 1987	C.A. McDevitt F.R. Steward J.E. Venart	University of New Brunswick Mechanical Engineering Department	- offers two explanations of BLEVE's	- article points out that BLEVE is often used instead of the word explosion even though they are different things	- since accident reports have inadequate information experiments are needed to determine which mechanism is responsible for BLEVE's	- article restates the superheat limit theory - offers a second theory as well, this theory that the homogenious boiling occurs at the rupture location only as the liquid meets the air
Hazards and Protection of Pressure Storage and Transportation of LP-gas 1988	J.A. Davenport	Industrial Risk Insurers	- offers expanation of BLEVE's	- BLEVE's occur more frequently and faster when fire impinges on the vapour space than when fire impinges on the liquid space	- no recommendations	- no comments
BLEVE: The Propane Cylinder 1988	V. Dunn	NY Fire Department	- offers expanation of BLEVE's - give information about time to BLEVE	- due to weakening of the metal from high temperatures BLEVE's can occur even if the pressure relief system operates properly	- no recommendations	- no comments

4-0 Research Needs

This literature review has found many articles who's authors make recommendations for further research. These recommendations are outlined below.

4-1 Projectile Hazards

Authors of reports reviewed in this study have made the recommendation that more data on projectile hazards is needed. Holden and Reeves (1985) noticed a trend that the size of PLG vessels has an effect on the distance that fragments are hurled. They state that more data is required to determine the relationship between vessel size and fragment distance hurled. Holden (1986) recommends that more parameters need to be investigated than is possible through accident reports. He stated that more data is needed on the following parameters: angle of launch, distance thrown until first bounce and the direction of launch with respect to the tank axis. Baum (1988) also observed a lack of data on PLG container failure.

Short comings in the ability of models to predict missile behaviour from PLG tank explosions exist. Baum (1984a and 1988) note that current models make the unreasonable assumption that no fluid leakage between fragments occurs in the launch stage. This means that these models give impossible to attain upper limits which are not useful. Baum (1988) has found that many possible missile generation patterns for PLG vessels do not even have crude models for prediction. He states that model development is needed in this area. Baker also recommends modelling studies be conducted to improve the state of knowledge for the prediction of projectile behaviour (see figure 8).

4-2 Blast and Projectile Effects on Structures

Pritchard (1983) recommends the aerodynamic characteristics of

deforming structures be investigated and that more explosion tunnel tests be conducted on a wider variety of dimensions and loads.

Jowett (1986) recommends that some areas of projectile penetration into concrete and metal barriers need further work. These areas include: the influence of target welds, the effect of non normal impact and the difference between thin flat targets and thin curved targets.

4-3 Vessel Failure Modes

Many articles or reports have been written on the failure modes of PLG vessels. These reports include: Anderson and Norris (1974), Early and Interrante (1975), Christ (1979), Charlton and Heslop (1984), Baker (1984b), Baum (1984a), Schulz-Forberg et al (1984) and McHenry et al (1987). All these reports, with the exception of McHenry (1987) deal with tanks where rupture began in an axial direction and then at some point or points the cracks branched in the circumferential direction generating fragments (see figure 14). The report by McHenry et al (1987) deals with a process cylinder where rupture began in a circumferential direction and remained that way (ie a head blew off). This would be classified as a rupture pattern F-1 under Westin's (1971) rupture configuration classification system. While no recommendations were made to conduct research into failure modes, the determining factors that govern which rupture configuration occurs in an explosion are not understood.

4-4 BLEVE Phenomena

Both Reid (1979) and McDevitt et al (1987) contain a recommendation to conduct experiments into the mechanism of BLEVE's. Reid (1979) presents the superheat limit theory and

recommends that a well conceived experiment be conducted to prove or disprove this theory. McDevitt et al (1987) emphasizes the need to conduct experiments to show which of the three possible mechanisms they present is responsible for BLEVE's.

4-5 Fire Ball Hazards

Pietersen (1988) states that the fire ball characteristics of BLEVE explosions are not accurately predictable and model development should be carried out.

5-0 Conclusions And Recommendations

This literature review has investigated the state of knowledge of the failure of PLG vessels. The 'accident phase' (see figure 3) of the events during a PLG accident is understood well. This literature search assessed the knowledge of mainly the 'release phase' and briefly the "hazard phase". Specific areas of interest were, the effect of initial conditions on ruptures, the ability to predict BLEVE's and the hazards from explosions such as blast waves and missile generation.

This review has concluded that there is one area where knowledge is good, a couple of areas where knowledge is weak and several areas where there is little knowledge:

1) There is a good understanding of the characteristics of fire balls from non-BLEVE events. There are several models available for non-BLEVE fire balls that have been shown to be accurate for full scale events.

2) There is some understanding of the following topics: the effects of blast on structures and the common failure modes for rupturing PLG containers.

   The prediction of the blast effects on structures has progressed from the qualitative blast damage tables to more vessel specific knowledge such as the one fortieth scale cylinder blast tunnel experiments conducted by Brown and Nolan (1985). These tests help further our understanding of the effects of PLG container explosions on neighboring cylinders. One model is available for blast effects on cylinders. However this model is based only on small scale studies.

   There are two common failure modes for PLG container explosions. The most common is, where the rupture begins in the axial direction and then branches in the circumferential

direction to form various types of fragments. This common failure mode of PLG storage vessels has been well documented. This mode can generate a number of different specific failure patterns and have been categorized into 7 different failure patterns by the number and type of fragments generated Westin (1971). The other common failure mode for PLG containers is, rupture begins in the circumferential direction and remains that way generating one or two tubs. Westin (1971) categorizes two different failure patterns for this mode. What determines which of these failure modes and patterns occur is still not understood.

3) Some topics of interest have been found where there is a definite lack of knowledge. Topics in this category include: projectile hazards, the effects of fill level on the severity of an explosion or the likely hood of a BLEVE, the characteristics of BLEVE fire balls and the mechanism of the BLEVE itself.

No validated model exists to predict the hazards from PLG container projectiles. In most cases only unreasonably conservative estimates of upper limits for the distance fragments are hurled exist (Baum, 1988). Two equations for reasonable upper limits for fragment velocity are available but they are not validated. Baum (1988) states in his notes to figure 12 (of this report) that he expects the fill level to have an effect on the projectile hazards but what kind of an effect is not known. Effects of the fill level in the PLG vessel at the time of rupture on the severity of the explosion have not been investigated.

Pietersen (1988) points out that the accuracy of predicting fire balls from BLEVE events is poor. He states that there are many validated models for predicting non-BLEVE fire balls but none that has been validated for specifically BLEVE events.

Several theories for the mechanism of BLEVE's have been advanced but no experimental evidence has been used to support them. No one theory can be said to be more accurate than the others until experiments are conducted to investigate them.

Work should be conducted to help understand the characteristics of fire balls from BLEVE events. More data is also needed to predict the likely hood of different failure modes occurring. A validated model for the prediction of projectile hazards should be developed. This model should be able to predict the distance thrown, the size and the kinetic energy for fragments generated from a PLG container explosion. The model should use parameters such as tank size internal temperature, internal pressure and the tank fill level at the time of rupture to predict the projectile hazards.

Based on the findings of this study the following research projects are proposed:

1) Initiate an experimental program consisting of exploding PLG vessels by fire engulfment. This project would investigate the effects of fill level on the severity of the explosion, the failure mode and the projectile hazards. This would also help to create a model to predict the fire ball characteristics from BLEVE's. Information from this experimental program would help fire fighters and storage plant designers.

2) Based on the findings of the above experiments develop a computer model to predict catastrophic failure modes and failure patterns of PLG containers. The model would use information about the conditions at rupture to predict the failure mode likely to occur, as well as the direction, size and distance the generated fragments would be thrown. This model would use data from the above experimental program and

accident case studies for validation. Such a model could be useful in designing future transportation and storage vessels.

3) Develop a theory supported by evidence to explain the mechanism of a BLEVE. This theory should explain what causes a BLEVE, the mechanism by which it occurs and what parameters influence its occurrence. With such information it may one day be possible to design 'BLEVE suppressors', or at least improve vessel designs to reduce the occurrence of BLEVE's or their effects.

4) Use fire ball measurements from the experimental program to create a model to predict fire ball characteristics for BLEVE events. This model would use information about the parameters governing the mechanism of a BLEVE and the vessel contents at the time of rupture to predict the required fire ball characteristics (size, duration, and heat flux). Such a model would prove useful for storage site and transportation route planning.

REFERENCES

Anderson, C.E. and Norris, E.B., 1974 "Fragmentation and Metallurgical Analysis of Tank Car RAX 201" Report No. FRA-OR&D 75-30, Federal Railroad Administration, Washington, DC

Appleyard, R.D., 1980, "Testing and Evaluation of the Explosafe System as a Method of Controlling the BLEVE", Report No. TP 2740, Transport Canada

Audemir, N.U., Magapu, U.K., Sousa, A.C.M. and Venart, J.E.S., 1988, "Thermal Response Analysis of LPG Tanks Exposed to Fire", *Journal of Hazardous Materials*, Vol. 20, pp. 239 - 262

Baker, W.E., 1984a, "Blast and Fragments From Bursting Pressure Vessels", *ASME Pressure Vessel and Piping Division*, Vol. 82, pp. 51 - 66

Baker, W.E., 1984b, "Post Test Assessment of Blast and Fragment Effects of Explosive Failure of a Large Steel Containment Shell Model During Pneumatic Testing", *ASME Pressure Vessel and Piping Division*, Vol. 82, pp 289 - 296

Baker, W.E., Westine, P.S. and Cox, P.A., 1978, "Methods For Prediction of Damage to Structures From Accidental Explosions", *International Conference on the Transportation and Storage of LPG and LNG*, Brugge, pp. 339 - 346

Baum, M.R., 1984a, "The Velocity of Missiles Generated By The Disintegration of Gas Pressurized Vessels and Pipes", *ASME Pressure Vessel and Piping Division*, Vol. 82, pp. 67 - 83

Baum, M.R., 1984b, "Large Missiles Generated by the Rupture of Gas Pressurized Vessels: A Summary of Current Data From Experiments at CEGB, Berkeley Nuclear Laboratories", *ASME Pressure Vessel and Piping Division*, Vol. 82, pp. 39 - 50

Baum, M.R., 1988, "Disruptive Failure of Pressure Vessels: Preliminary Design Guidelines for Fragment Velocity and Extent of the Hazard Zone", *Journal of Pressure Vessel Technology*, Vol. 110, pp. 168 - 176

Bettis, R.J., 1982, "Two Phase Flashing Releases Following Rapid Depressurization Due to Vessel Failure", *The Assessment of Major Hazards, Institute of Chemical Engineers Symposium Series No. 71*, Manchester, UK, pp. 247 - 263

Billinge, K., Moodie, K. and Beckett, H., 1986, "The Use of Water Sprays To Protect Fire Engulfed LPG Storage Tanks", *4th International Symposium On Loss Prevention*, pp. 47-1 - 47-21

Birk, A.M., 1988, "An Experimental Investigation of a Cylindrical Vessel Engulfed in Fire With a Burning Relief Valve Flare Present", *ASME Proceedings of the 1988 National Heat Transfer Conference*, pp. 125 - 135

Board, S.J., Hall, R.W. and Hall, R.S., 1975, "Detonation of Fuel Coolant Explosions", *Nature*, Vol. 254, pp 319 - 320

Brossard, J., Leyer, J.C., Desbordes, D., Garnier, J.L., Hendrickx, J., Perrot, J. and Saint-Cloud, J.P., 1983, "Experimental Analysis of Unconfined Explosions of Air Hydrocarbon Mixtures - Characterization of the Pressure Field", *Institute of Chemical Engineers Symposium Series No. 80*, pp. D10 - D19

Brossard, J., Duco, J., Gobert, T., Lannay, A. and Perrot, J., 1986, "Experimental Study of the Overpressures Generated By the Detonation of Spherical Air Hydrocarbon Gaseous Mixtures", *GASTECH 1986*, pp. 158 - 171

Brown, D.M. and Nolan, P.F., 1985, "The Effect of External Blast on Cylindrical Structures", *The Assessment and Control of Major Hazards, Institute of Chemical Engineers Symposium Series No. 93*, Manchester, UK, pp. 229 - 245

Charlton, R.S. and Heslop, I.M., 1984, "Summary Report on Propane Bulk Truck Rupture Near Salmon Arm, B.C. June 13, 1984", Report No. TP6523E, Transport Canada Transport Dangerous Good Directorate, Ottawa, ON

Christ, B.W., 1979, "Analysis of the Pneumatic Bust of a Large Seamless Steel Pressure Vessel in Natural Gas Service", Report No. DOT/RSPA/MTB - 78/4, U.S. Department of Transport, Washington, DC

Collins, G.R., 1986, "BLEVE in an LPG storage yard", *Fire Command*, September, pp. 18 - 21

Crocker, W.P. and Napier, S.H., 1989, "Assessment of Mathematical Models For Fire and Explosion Hazards of Liquefied Petroleum Gases", *Journal of Hazardous Materials*, Vol. 20, pp. 109 - 135

CTC Railway Transport Commitee Operations Branch, 1986, "1986 Summary of Railway Accidents / Incidents as Reported to the Canadian Transport Commission", Canadian Transport Commission Railway Transport Committee

Davenport, J.A., 1988, "Hazards and Protection of Pressure Storage and Transportation of LP-gas", *Journal of Hazardous Materials*, Vol. 20, pp. 3 - 19

Dunn, V., 1988, "BLEVE: The Propane Cylinder", *Fire Engineering*, August, pp. 63 - 70

Early, J.G. and Interrante, C.G., 1975, "A Metallurgical Investigation of a Full Scale Insulated Rail Tank Car Filled With

LPG Subjected to a Fire Environment", Report No. FRA OR&D 75-32, Federal Railroad Administration, Washington, DC

Flecher, B., 1982, "Sudden Discharge of a Superheated Fluid to Atmosphere", *The Assessment of Major Hazards, Institute of Chemical Engineers Symposium Series No. 71,* Manchester, UK, pp. 25 - 37

Grange, G.M., 1980, "Report of the Mississauga Railway Accident Inquiry", Report No. T22-50/1981E, Canadian Transport Commission

Graves, K.W., 1973,"Development of a computer Program For Modeling the Heat Effects on a Railroad Tank Car", Report No. FRA OR&D 75-33, Federal Railroad Administration, Washington, DC

Holden, P.L., 1986, "Assessment of Missile Hazards: Review of Incident Experience Relevant to Major Hazard Plant", Report No. SRD R 477, United Kingdom Atomic Energy Authority

Holden, P.L. and Reeves, A.B., 1985, "Fragment Hazards From Failures of Pressurized Liquefied Gas Vessels", *The Assessment and Control of Major Hazards Institute of Chemical Engineers Symposium Series No. 93,* Manchester, UK, pp. 205 - 220

Jones, M.R.O., 1985, "Vapour Explosions Resulting From Rapid Depressurization of Liquids - the Importance of Initial Temperature", *Institute of Chemical Engineers Symposium Series No. 93,* Manchester, UK, pp. *357 - 362*

Jowett, J., 1986, "The Effects of Missile Impact on Thin Metal Structures", Report No. SRD R 378, United Kingdom Atomic Energy Authority

Lihou, D.A. and Maund, J.K., 1982, "Thermal Radiation Hazard From Fire Balls", *The Assessment of Major Hazards Institute of Chemical Engineers Symposium Series No. 71,* Manchester, UK, pp. 191 - 224

Magee, J., 1985, "Report of the Inquiry into the Failure of UTLX 9846 on Feb 28 1984 in the CN Company's MacMillan Yard in the Township of Vaughan Ontario", File No. D. C. 15.7.13, Canadian Transport Commission

Manda, L.J., 1971, "Effects of Fire on LPG Tank Cars", Report No. RA-11-1-5, Railroad Tank Car Safety Research and Test Project, Chicago, IL

Manda, L.J., 1973, "Phase 11 Report on Analysis of 1/5 scale Fire Tests", Report No. RA-11-5-26, Railroad Tank Car Safety Research and Test Project, Chicago, IL

Manda, L.J., 1975, "Full Scale Fire Tests Railroad Tank Car Safety", Report No. RA-11-6-31 Research and Test Project, Chicago, IL

Martinsen, W.E., Johnson, D.W. and Terrel, W.F., 1986, "BLEVE's Their Causes Effects and Prevention", *Hydrocarbon Processing*, November, pp. 141 - 148

Maurer, B., Hess, K., Giesbrecht, A. and Leuckel, W., 1978, "Modeling of Vapour Cloud Dispersion and Deflagration After Bursting of Tanks Filled With Liquefied Gas", *2nd International Symposium on Loss Prevention in the Process Industries*, Heidelberg, pp. VI 303 - VI 321

McDevitt, C.A., Steward, F.R. and Venart, J.E., 1987, "What Is a BLEVE?", *The 4th Technical Seminar on Chemical Spills Proceedings*, February 1987, Toronto, ON

McHenry, H.I., Read, D.T., and Shives, T.R., 1987, "Failure Analysis of an Amine - Absorber Pressure Vessel", *Materials Performance*, pp. 18 - 24

Moodie, K., 1988, "Experiments and Modeling: An Overview With Particular Reference to Fire Engulfment", *Journal of Hazardous Materials*, Vol. 20, pp. 149 - 175

Moodie, K., Billinge, K. and Cutler, D.P., 1985, "The Fire Engulfment of LPG Storage Tanks", *The Assessment and Control of Major Hazards, Institute of Chemical Engineers Symposium Series No. 93*, Manchester, UK, pp. 87 - 106

Moodie, K., Cowley, L.T., Denny, R.B., Small, L.M. and Williams, I., 1988, "Fire Engulfment Tests on a 5 Tonne LPG Tank", *Journal of Hazardous Materials*, Vol. 20, pp. 55 - 71

Moorhouse, J. and Pritchard, M.J., 1982, "Thermal Radiation Hazards From Large Pool Fires and Fire Balls - A Literature Review", *The Assessment of Major Hazards Institute of Chemical Engineers Symposium Series No. 71*, Manchester, UK, pp. 397 - 428

Munday, G., 1980, "Initial Velocities Attained By Plant Generated Missiles", *Nuclear Energy*, Vol. 19, pp. 165 - 169

Neilson, A.J., 1985, "Empirical Equations For the Perforation of Mild Steel Plates", *International Journal of Impact Engineering*, Vol. 3, No. 2, pp 137 - 142

O'Donoghue, D.E., Predebon, W.W. and Anderson, C.E., 1988, "Dynamic Launch Process of Preformed Fragments", *Journal of Applied Physics*, Vol. 63, January 15, pp. 337 - 348

Peterson, R.J., Grewal, S.S. and El-Wakil, M.M., 1984, "Investigations of Liquid Flashing and Evaporation due to Sudden Depressurization", *International Journal of Heat and Mass Transfer*, Vol. 27, No. 2, pp 301 - 310

Pietersen, C.M., 1988, "Analysis of the LPG Disaster in Mexico City", *Journal of Hazardous Materials*, Vol. 20, pp. 85 - 107

Phillips, E.A., 1985, "Effectiveness of Shelf Couplers, Head Shields and Thermal Shields on DOT 112(114) and 105 Tank Cars", Report No. RA-02-5-51 Railroad Tank Car Safety Research and Test Project, Chicago, IL

Pohto, H.A., 1979, "Energy Release From Rupturing High Pressure Vessels: A Possible Code Consideration", *Journal of Pressure Vessel Technology*, Vol. 101, May, pp 165 - 170

Porter, W.H.L., 1980, "Generation of Missiles and Destructive Shock Fronts and Their Consequences", *Nuclear Energy*, Vol. 19, No. 3, pp 171 - 177

Prause, R.H., Sullivan, J.W. and Eiber, R.J., 1972, "Analysis of Tank Car Tub Rocketing in Accidents", Report No. RA-12-2-23, Railroad Tank Car Safety Research and Test Project, Chicago, IL

Pritchard, D.K., 1983, "An Experimental and Theoretical Study of Blast Effects on Simple Structures (Cantilevers)", *4th International Symposium on Loss Prevention and Safety Promotion in the Process Industries, Institute of Chemical Engineers Symposium Series No. 82*, pp. D23 - D32

Qureshi, G., 1984, "Experimental Determination of the Heat Transfer in the Vapour Space of a Partially Filled Horizontal Cylinder", Report No. UNB-ME-TF-27, University of New Brunswick Mechanical Engineering Department, Fredricton, NB

Reedy, C.E., 1970, "Sequence of Events Following Crescent City Derailment", Report No. RA-01-1-1, Railroad Tank Car Safety Research and Test Project, Chicago, IL

Reedy, C.E., 1971, "Sequence of Events Following Houston Texas Derailment", Report No. RA-03-3-9, Railroad Tank Car Safety Research and Test Project, Chicago, IL

Reid, R.C., 1979, "Possible Mechanism for Pressurized - Liquid Tank Explosions or BLEVE's", *Science*, Vol. 203, March, pp. 1263 - 1265

Roberts, A.F., 1982, "The Effect of Conditions Prior to Loss of Containment on Fire Ball Behaviour", *The Assessment of Major Hazards Institute of Chemical Engineers Symposium Series No. 71*, Manchester, UK, pp. 181 - 190

Roberts, A.F., Cutler, D.P. and Billinge, K., 1983, "Fire Engulfment Trials With LPG Tanks With a Range of Fire Protection Methods", *Proceedings of the 4th International Symposium on Loss Prevention and Safety Promotion in the Process Industries, Institute of Chemical Engineers Symposium Series*, No. 82

Schoen, W. and Droste, B., 1988, "Investigation of Water Spraying Systems For LPG Storage Tanks by Full Scale Fire Tests", *Journal of Hazardous Materials*, Vol. 20, pp. 73 - 82

Schulz-Forberg, B., Droste, B. and Charlett, H., 1984, "Failure Mechanisms of Propane Tanks Under Thermal Stresses Including Fire Engulfment", *International Conference on Storage and Transport of LPG and LNG*

Scilly, N.F., High, W.G., 1986, "The Blast Effects of Explosions", *4th International Symposium on Loss Prevention,* pp. 39-1 - 39-15

Skogsberg, A.M., 1971, "Review of Literature and Related Experience", Report No. RA-04-1-8, Railroad Tank Car Safety Research and Test Project, Chicago, IL

Taylor, D.E. and Price, C.F., 1971, "Velocities of Fragments From Bursting Gas Reservoirs", *Journal of Engineering for Industry*, November, pp. 981 - 985

Townsend, W., Anderson, C., Zook, J. and Cowgill, G., 1974, "Comparison of Thermally Coated and Uninsulated Rail Tank Cars Filled With LPG Subjected to a Fire Environment", Report No. FRA OR&D 75-32, Federal Railroad Administration, Washington, DC

Tulacz, J. and Smith, R.E., 1980, "Assessment of Missiles Generated by Pressure Component Failure and its Application to Recent Gas Cooled Nuclear Plant Design", *Nuclear Energy*, Vol. 19, June, pp. 151 - 164

Van der Schaaf, J.B.R. and Steunenberg, C.F., 1983, "Investigation into the circumstances Surrounding an Accident in Nijmejen Involving a Tanker", *Institute of Chemical Engineers Symposium Series No. 80,* pp. N14 - N23

Van Wingerden, C.J.M. and Zeeuwen, J.P., 1986, "Vapour Cloud Explosion Experiments For Use in Hazard Assessment", *4th International Symposium on Loss Prevention,* pp. 37-1 - 37-12

Venart, J.E.S., 1985, "Tank Car Thermal Response Analysis: Executive Summary: Volume 1", Report No. TP 6809E, Transport Canada

Walls, W.L., 1979, "The BLEVE Part I & II", *Fire Command*, May, pp. 22 -24, June pp. 35 - 37

Westin, W.E., 1971, "Summary of Ruptured Tank Cars Involved in Past Accidents", Report No. RA-01-2-7 Railroad Tank Car Safety Research and Test Project, Chicago, IL

Zeeuwen, J.P., Van Wingerden, C.J.M. and Dawe, R.M., 1983, "Experimental Investigation Into Blast Effects Produced By Unconfined Vapour Cloud Explosions", *Institute of Chemical Engineers Symposium Series No. 80,* pp. D20 - D29